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RESEARCH IN THE DEVELOPMENT OF INTEGRATED WINDPOWER SYSTEMS AND SYNCHRONOUS INVERTERS

Prepared for

MONTANA DEPARTMENT of NATURAL RESOURCES and CONSERVATION

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RESEARCH IN THE DEVELOPMENT OF INTEGRATED WINDPOWER SYSTEMS AND SYNCHRONOUS INVERTERS

Prepared by

V. Hugo Schmidt o-WLN
Physics Department
Montana State University
Bozeman, MT 59717

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I. Objective

The primary purpose of this project was continued design, development, and testing of synchronous inverters for converting wind-generated dc power to alternating current which can be fed into the utility grid. Small inverters suitable for individual homeowners or ranchers were studied.

II. Project Implementation

A. Introduction

Wind-generated electricity can be stored, used immediately by the producer, or fed into the power line. For storage, it must be generated as, or converted to, dc (direct current). An ordinary inverter must then be used to operate 120-volt ac (alternating current) equipment. Immediate use without storage capability appears, because of the wind's intermittent nature, to be limited chiefly to supplemental heating. For widespread use to be made of wind-generated electricity nowadays, when almost all locations have commercial power available, it is necessary to tie the wind generators into the utility grid.

Several methods have been investigated for incorporating wind generators into power grids.[1] Rotary ac-dc-ac or dc-ac converters are too expensive. Constant-speed synchronous alternators or nearly-constant-speed induction alternators require variable pitch control to keep the rotor speed constant. Ramakumar and Hughes[2] at Oklahoma State University are experimenting with field-modulated variable speed generators, in which the modulation provides a 60-Hz component in the output regardless of generator speed. Finally, dc can be converted electronically into 60-Hz ac synchronized with the power grid by means of synchronous inverters. Only one model is commercially available at present, the Gemini Synchronous Inverter sold by Windworks at Mukwonago, Wisconsin. It employs an SCR (silicon-controlled rectifier) bridge and control circuitry to achieve the desired load on the generator by adjusting the SCR fiting time relative to the phase of the ac voltage. This unit operates on 220-volt single phase power, is rated at 8 kW, and costs $1,295.

This report begins with a description of work done by us prior to this Grant, continues with a discussion of our SCR-based inverter and of such inverters in general, followed by a description of our present transistorized inverter and its performance. A description of our proposed higher-power transistorized inverter follows. Other work done under this Grant is then detailed. The report concludes with a brief description of future plans.

B. Work done by us prior to this Grant

We began work on wind energy systems in 1973. First we built a transistorized synchronous inverter with the circuit shown in Fig. 1. We then built the wind generation system shown in Fig. 2. This system has been in continuous operation since 1974, and has been used with the above synchronous inverter since 1975. The inverter is quite small, with only 60 watts output and 100 watts input (60% efficient), while the Delco automotive generator can produce over 500 watts, so batteries are used to absorb the excess power over 100 watts. The system has been quite reliable.

Bench tests were made of the Delco alternator. When used with a 14 volt automotive voltage regulator, the maximum efficiency was 46%. Without the regulator it was possible to reach 64% efficiency, at 30 amps and 30 volts, or 900 watts. The system shown in Fig. 2 is used with the voltage regulator. The electrical power out of the alternator was found to be 30% of the available wind power for a wind speed of 18 mph. Here available wind power is defined as 16/27 of the kinetic energy of air/passing through a circle of 8-foot diameter at the speed indicated by the anemometer, which is the theoretical maximum for a wind rotor of that diameter. Accordingly, the rotor and drive train mechanical efficiency come out to 30%/46% = 65%, somewhat higher than expected for a rotor of this type. Details of this system are available upon request, and the system is available for inspection on top of the Physics Building at Montana State University; anyone wishing to see it should contact me.

We tested a Gemini Synchronous Inverter which AERO (Alternative Energy Resources Organization) kindly loaned to us. Gemini claimed an efficiency of about 98% for this unit. This claim is probably correct as far as the unit itself is concerned, because the unit is basically an SCR bridge, and SCR's are essentially electronic switches which dissipate little power. However, the current waveform from the Gemini unit consists of sharp spikes unless large inductors are used to smooth the current. The high current during these short-duration spikes results in a large I^2R heat loss inside the generator, so that for the same mechanical power input to the generator, the power delivered to the ac line is considerably lower than the power which the generator could deliver directly to a resistive load. We found that the system efficiency, defined as power to the ac line divided by power available for a resistive load, could be as low as 50%.

We also made a fairly extensive theoretical study of system efficiencies which can be attained for such SCR-type synchronous inverters, as functions of the ratio of the dc voltage to the ac line voltage, the SCR firing angle, and the quality factor Q for the inductance/resistance ratio of the dc circuit. Results of this analysis are available upon request.

C. SCR-Type Synchronous Inverter

Before the beginning of this Grant, we had partially constructed a synchronous inverter based on an SCR (silicon-controlled rectifier) bridge. This inverter is shown in Fig. 3. As described in the proposal for this Grant, we intended further development and test of this inverter. We were aware of two drawbacks of this type of circuit. First, both terminals of the generator must be floating, so if an automotive generator or alternator is used it must be modified so that the case is insulated from the negative terminal, or else one must accept the risk associated with the case being at a varying voltage of order 100 volts with respect to ground. Second, the current into the ac line will consist of spikes or short pulses of alternating polarity unless a large and low-loss inductor is used, in which case the current waveform can approach a square wave. With the simple SCR bridge circuit used in this unit and also in the Gemini unit, it is not possible to feed a sinusoidal current into the line. Early in 1977 a visitor from Pennsylvania (whose name I can't locate) who is active in wind energy told me that the utilities in that state are opposed to connecting Gemini synchronous inverters into the grid because of their poor current waveform. If such inverters were used on a large scale, they would distort the waveform for the power grid. For these reasons I decided to go back to the transistorized synchronous inverter design.

D. Present Transistorized Synchronous Inverter

A photograph of our present transistorized synchronous inverter and associated test equipment is shown in Fig. 4, while a circuit diagram appears in Fig. 5. This unit is similar in principle to, but considerably larger, than, our first unit which is in operation on the roof of the Physics Building. The circuit is based on two transformers and two transistors. The unit is described as an inverter because it changes dc power into ac power. It is called a synchronous inverter because the circuit is driven synchronously at the same frequency as that of the ac line. This eliminates any change in frequency from line frequency which would occur with a self-oscillating circuit.

To understand how the circuit operates, consider first the voltage waveform applied by one end of the input transformer T_1 to the base of transistor A, as shown in Fig. 6. A dc bias is applied to the center tap of transformer T_1 by the voltage divider consisting of the 1400 ohm variable resistor and the 10 ohm resistor which is connected between the center tap and ground. This bias insures that one transistor turns on at the instant that the other transistor turns off, and eliminates crossover distortion in the output current waveform. Specifically, the dc bias is just equal to the forward V_{BE} drop of the transistor, so that the transistor turns on as soon as the ac component of the base voltage becomes positive. The 0.01 ohm resistor in the emitter lead provides a voltage proportional to emitter current for test purposes.

When the voltage on the base of transistor A is on the positive half of its cycle, transistor A is turned on, while transistor B is turned off because its base voltage is on the negative half of its cycle. When transistor A is on, it allows a current to flow from the dc source (alternator with rectifying diodes in its case) in the "up" direction through two of the parallel windings of transformer T_2 shown in Fig. 5, then through transistor A and the 0.01 ohm resistor to ground. This current is sinusoidal because the base current and voltage are sinusoidal and the transistors and transformer are operating in the linear range.

On the other half of the ac cycle, the voltage on the base of transistor B is on the positive half of its cycle. Then transistor B is on, allowing current to flow in the "down" direction through the other two parallel windings in the primary of transformer T_2, thence through transistor B and the 0.01 ohm resistor to ground. Over the entire cycle, thus, there are two sinusoidal half-waves of current flowing in opposite directions through primary windings of transformer T_2. Accordingly, the magnetic core of the transformer responds as if a sinusoidal alternating current were flowing in the primary. This changing magnetic field induces a voltage in the secondary which opposes, and is greater than, the 120 volt, 60 Hz line voltage of the house line connected to the secondary. A current thus flows into the line which is equal to the voltage difference divided by the effective resistance of the inverter. The power fed back into the line is measured by the rate at which the watt-hour-meter runs backwards.

A variable transformer is shown in Fig. 5 controlling the ac voltage to the primary of transformer T_1. By this means, the base current to transistors A and B is controlled. These base currents are proportional both to the collecter currents which flow through the primary of transformer T_2, and to the output current from the secondary of T_2 into the line. This arrangement is convenient for test purposes, but in actual operation will have to be replaced by a circuit which controls the base current in such a way as to feed the maximum power back into the line at each wind speed. This circuit is not yet fully designed, but its principle of operation is simple. First, one notes that for a given wind speed, u, the power delivered to the wind rotor is a function of the rotor tip speed, v. This function depends on the rotor aerodynamics, but has the general shape shown in Fig. 7. The power is of course zero if the rotor is kept from turning, and is again zero at the free-wheeling speed it attains if disconnected from its load. One would like to operate at the peak of the power curve, and the tip speed at which this peak occurs will increase nearly linearly with wind velocity. With a fixed load, as occurs for a generator with voltage regulator feeding batteries or a heater, at a low wind speed just above that required for the generator to "cut in" and start generating power the load will be greater than the rotor can supply, so the rotor will slow down until the generator "cuts out". In a steady wind of this speed, the generator will alternately cut in and out, rather than run at a constant speed. In a strong wind, the rotor will speed up almost to its free-wheeling speed before the rotor power output falls to the load power required. Both modes of operation have been observed for the wind generating system on top of the Physics Building, which has a fixed load. From Fig. 7 it is obvious that if a fixed-load system is optimized for one wind speed (about 18 mph in this Figure), its efficiency falls rapidly as wind speed deviates from this optimum value.

In designing the control circuit, one notes that the peak rotor power varies approximately as u^3 (the kinetic energy of a given volume of air varies as u^2, while the volume of air approaching the rotor per unit time varies as wind speed u). If the rotor is to run at its optimum speed, the power required by the inverter (plus mechanical drive losses and electrical losses in the generator) must then vary approximately as the cube of the tip speed v. This speed is proportional to the generator rpm. Fortunately the Delco alternator has a terminal which supplies ac voltage at a frequency proportional to its rpm. This signal can be converted to a dc voltage proportional to the frequency (or rpm) by standard electronic techniques. For an ideal lossless generator and mechanical drive, one would want the dc power into the inverter to vary as v^3. For our circuit it is desirable to keep the dc input voltage fixed, so the input current then would go as v^3.

Our alternator is non-ideal for two main reasons. First, the stator output coils have a resistance of about $\frac{1}{2}$ ohm, with corresponding I^2R heat loss. If the current I varies as v^3, the heat loss will vary as v^6, so that efficiency will be reduced at high power levels. From this standpoint it is desirable to operate at high dc voltage V and low current I to obtain a given power VI. But this conflicts with the desire to keep the alternator field power low, because the alternator emf ($V + IR_s$, where R_s is the stator resistance) is proportional to vI_f, the product of alternator rpm and field current. The current I_f must be controlled by a voltage regulator, which increases I_f as generator speed drops. The voltage regulator absorbs a power greater than VI_f, which is roughly proportional to V^2/v, so especially at low wind speeds it is desirable to reduce the operating voltage.

Our present circuit shown in Fig. 5 is designed for the intermediate power range. In order to operate at a higher voltage than the 14 volts governed by a standard voltage regulator, we have a zener diode and bypass resistor so that the regulator keeps its input at 14 volts, while the other end of the zener diode which is at the inverter input is 10 volts higher. Because the zener diode only allows current to flow when more than 10 volts is applied across its terminals, the bypass resistor is essential to allow field current to flow during alternator voltage build-up.

The capacitors at the inverter input improve system efficiency in two ways. First, they keep the input voltage to the inverter nearly constant over the ac cycle. The inverter is more efficient if its input voltage does not drop at the peaks of the ac cycle because of the increased current required then and the corresponding IR_s drop in the alternator. (The magnetic response of the alternator field is not fast enough to allow the voltage regulator to keep the output voltage constant over the cycle.) The capacitors also allow the alternator to supply current at a more uniform rate, thereby reducing the I^2R_s loss in the alternator.

In actual operation this circuit would include relays to prevent waste of ac power at low wind speed, and energizing of the ac line by the wind system in the event of power failure. For low wind speed, when the generator cuts out a dc relay will open, interrupting power to an ac relay which operates off line voltage and which connects the inverter to the ac line. Such relays, which are part of the inverter now in operation in the rooftop system, prevent a small but continuous power drain into the inverter during low wind periods. In principle the synchronous inverter should not operate if the ac line goes dead, because the line supplies the necessary ac signals to the bases of the transistors. However, with a dc power source connected to the inverter, there is always the possibility that the circuit will turn into an oscillator with an arbitrary voltage and frequency, especially if there happens to be little or no load connected to the dead portion of the line. For the protection of any lineman working on the supposedly dead line and any equipment connected to that line, it would be desirable to arrange for the above-described ac relay to be operable only if the voltage applied to it is near 120 volts in magnitude and 60 Hz in frequency. This could be accomplished by putting the ac relay coil in series with the contacts of an ac overvoltage relay and making the coil part of a series resonant circuit tuned to 60 Hz.

In testing this circuit, we used an ac motor to drive a Delco alternator of the standard automotive type. In addition to monitoring the meters shown in Fig. 5, we used a dual-trace oscilloscope, with one probe connected to the 0.01 ohm emitter lead resistor to monitor the dc current, and the other to one of the transistor collectors. Typical waveforms are shown in Fig. 8. A nearly sinusoidal current, somewhat flattened at the peaks, was obtained for up to 150 watts input into the ac line. Above this power level, "second breakdown" occurred in the transistors. This breakdown is caused by too high a voltage and current in the transistor, is reversible, and takes place only if the voltage-current combination has been applied for too long a time (of order milliseconds). It creates a temporary short circuit between emitter and collector, and is responsible for the pips seen at the tops of the current waveforms. At the 200 watt output level, the pips became so large that operation at higher power seemed inadvisable, even though the transistors were not too hot to touch. In the 100 to 200 watt output range, the inverter efficiency ranged from 60 to 70%.

An analysis of the circuit will clarify why such efficiency is about as much as can be expected. The dc power supplied to the circuit is the product of the dc supply voltage and the dc current which has a rectified sinusoidal waveform as shown in Fig. 8. The dc power lost to heat in a transistor is the product of the collector voltage and the above dc current. At the beginning of the half-cycle that the transistor is on, the collector voltage is large but the current is small. At the middle of the cycle, the current is maximum but the collector voltage is small. If the collector voltage could drop sinusoidally to zero when the current reaches a sinusoidal maximum, the ratio of power loss to power input would be $1-\frac{1}{4}\pi$. Accordingly, the highest theoretical efficiency possible for this circuit is $\frac{1}{4}\pi$, or 78.54%. The actual efficiency is lower because the collector voltage must be maintained a minimum of a few volts above zero for proper operation, the transformer has resistance losses, and the alternator field requires power.

In summary, this inverter is capable of supplying a good sinusoidal current to the line, which is desirable from the utility's viewpoint. It has two deficiencies, low efficiency and low power output. The power output could be increased by putting transistors in parallel, because the output transformer is large enough to handle more power. It seems preferable, however, to try to increase the efficiency and power rating simultaneously. A proposed circuit to accomplish this is described in the following section.

E. Proposed Transistorized Synchronous Inverter

The above-described maximum theoretical efficiency of $\frac{1}{4}\pi$ is not peculiar to our present inverter circuit, but applies to any class A (linear, distortion-free) push-pull amplifier. Circuits for high-fidelity audio systems have recently been developed which operate at higher efficiency while preserving linearity. They incorporate two or more dc power supplies at different voltages. During the lower-current parts of the ac cycle the lower-voltage supply suffices to drive the system. When the peak current must be supplied, the signal is switched to another transistor driven by the higher-voltage supply. For our purposes it seems more practical to use one dc supply voltage and instead switch transformer taps and associated transistors at the desired points in the ac cycle. A circuit to accomplish this is shown in Fig. 9, and the expected waveforms to be obtained from this circuit are shown in

Fig. 10. The waveforms are based on our present transformer having a primary with four windings, each with the same number of turns. It will become evident that a different turns ratio would be preferable for this circuit.

During the first and last 30^o of the positive voltage half-cycle on the base of transistor T_1 this transistor is turned on, while transistor T_2 is kept off by transistor T_3 which during those intervals has a reverse-biased base-emitter junction. Current I_1 then flows to transistor T_1, which has a collector voltage V_1, if the forward drop across diode D_1 is ignored. The transformer turns ratio is such that at 30^o and 150^o V_1 is zero, so that transistor T_2 must be used in the interval between 30^o and 150^o. The voltage V_2 dips below the dc supply voltage V_0 only half as far as V_1 dips, and for the idealized situation shown in Fig. 10 it just dips to zero when the current I_2 reaches its maximum at 90^o phase. Because the step-up ratio from primary to secondary doubles upon switching from T_1 to T_2, twice as much current is required by T_2 at the instant of switching. This current ratio is provided by resistor R_4 which reduces the base current to T_1.

Transistor T_1 shuts off when its collector voltage becomes negative; diode D_1 prevents current flow in the forward direction through the base-collector junction of T_1. At the same time, V_1 becoming negative allows transistor T_3 to turn on, which then allows base current to flow to transistor T_2. Probably additional circuit elements will be needed to minimize the "glitch" in the output current associated with this switching. Resistors R_1 and R_2 provide the proper bias for switching smoothly between the positive and negative halves of the ac cycle, just as is done with the present synchronous inverter circuit.

In the graphs for the expected waveforms shown in Fig. 10, the current and voltage waveforms and their product which is the power loss to heat in the transistor are the same for transistor T_2 as for the present circuit. When transistor T_1 is on, its collector voltage is lower and its current is also lower than for the present circuit, so the power dissipation is much lower during this time than for the present circuit which has only one pair of transistors. The power dissipation would be still lower if the primary taps were relocated so that switching could be done at 45° instead of 30°. Providing additional transformer taps and transistor pairs can reduce the loss still further. In the impractical limit of an infinite number of taps and transistors, the idealized waveform losses go to zero. The effect of switching at various times on the power loss, input and output power, and efficiency is shown in Table I.

This circuit was proposed near the end of the Grant period covered by this report. It is being developed under our current DNR Grant, and further details will appear in the quarterly and final reports for that Grant.

F. Other Work Done Under This Grant

The major cause of friction in our present wind generation system shown in Fig. 2 is belt friction. Early last spring we replaced the belt, idler pulley, and alternator pulley with a $\frac{1}{2}$-inch pitch bicycle chain and sprockets. The friction was reduced by more than half, but other difficulties appeared. The chain was very noisy, and annoyed people in the Physics Building below. In high winds the chain would whip, and occasionally flip off without breaking. Upon consulting Marks' Handbook (which I should have done in the first place), I found that a shorter pitch, perhaps 3/8 inch, would have been preferable, but that it is difficult to operate a chain at the high lineal speed required by an automotive alternator. Accordingly, we abandoned the chain idea and went back to a $\frac{1}{2}$-inch wide standard fan belt. The trail cycle chain and sprockets which connect the hub to the idler shaft have given no problems. We grease the chain a few times a year and have had to tighten it once in four years. The belts have shorter life, perhaps a year or less. It is important to tighten the belt about every two months so that it will not slip on the alternator pulley during high winds. Other components of this system are holding up well after four years in spite of being exposed to the weather. However, the average wind speed on the Physics Building roof is only 4 mph, so in a windier location mechanical wear problems would show up much more quickly.

A second wind generation system, shown in Figs. 11 and 12, was constructed. This system has a downwind rotor and needs no tailfin. The rotor is mounted on a Buick front hub and has five short spars made of steel channel as shown in Fig. 11, to which are attached hollow tubular aluminum spars as shown in Fig. 12. The diameter of the rotor is 10 feet. Each spar holds a triangular Neoprene sail, with an eye at its apex to which is attached a cable running over a pulley at the end of the adjacent spar. The cable then runs down the inside of the spar to a spring. The spring has compressional preload so that a given tension, corresponding to the force caused on the cable by a wind of about 30 mph blowing on the sail, is required to stretch the spring.. This arrangement is intended to prevent rotor overspeed which could damage the rotor and alternator, and should also reduce the wind force on the sails in high winds.

As with the present system, a trail bike chain and sprockets drive the idler shaft, visible near the top of Fig. 11. A V-belt and pulleys then drive the alternator shown almost hidden behind the mainframe channel.

A vertical beam (not shown) will attach to the right end of the mainframe channel to allow the unit to be turned sideways to the wind so it can be stopped for repairs. Vertical axis rotation of the unit to face the wind is accomplished by the Rambler front hub shown in the front of Fig. 11. The assembly mounts on this hub through the holes visible in Fig. 11 just above the Rambler hub. The stationary part of the hub is mounted to a post by the adjustable clamp arrangement which appears below the hub. To bring dc power from the hub to the synchronous inverter, a brush and slip ring are used. The carbon brush is in a plastic housing at the right of the hub, and is attached to the fixed part of the hub. A copper band serving as slip ring is insulated from the rotating part of the hub by a piece of innertube.

To allow tests of this system in constant and controllable relative air speed, a tower was built for mounting this system on the bed of a pickup truck, as shown in Fig. 13. Construction is of 3/16 inch thick square welded steel tubes, with 1" x $\frac{1}{4}$" steel strap for cross-bracing. The top of the tower is attached to an aluminum tube, to which the vertical axis hub mounting bracket will be attached. At the bottom, the tower is bolted to steel channels, which in turn are bolted to two 4" x 4" pine timbers to be laid longitudinally in the truck box. The whole assembly will be rigidly attached to the truck, and tested only at low speed on calm days and abandoned highways. In these tests, the ac line will be a bank of 12 100-watt light bulbs supplied by an engine-driven 120 volt, 60 Hz alternator, so that it will be possible to test the system complete with synchronous inverter. These tests will be conducted this spring after the snow melts, and will be described in quarterly and final reports for the current DER Grant.

When the proposal for this Grant was written, we intended to test the second wind system at a location just southwest of the MSU stadium, where two log cabins with electric power are available for housing instrumentation and the synchronous inverters. However, this site became too popular for beer busts. The cabin door was found kicked open twice, and someone shot a hole in the anemometer we had mounted there. I searched for a more secluded location with electric power available, and found one west of the Vet Research Lab, about half a mile west of the MSU campus. This site is further described in reports for the current DNR Grant.

We continued keeping the weather records which we began taking in 1973. We measured the average daily wind speed by reading the totalizing anemometers daily, and dividing the mileage difference by the hours elapsed. These anemometers were located on top of the Physics Building and on a 15-foot high pole southwest of the MSU stadium. The average wind speeds at these locations are 4 and 7 mph respectively, corresponding to an available windpower ratio of $(7/4)^3$ or 5.4. We also recorded wind direction, temperature, and fraction of sky that was clear; the latter two records may be of interest for solar energy projects. In addition, we recorded daily the power output of the wind system on top of the Physics Building. All of these records are available upon request.

References:

1. R. Ramakumar and W. L. Hughes, in Proceedings of the Second Workshop on Wind Energy Conversion Systems, F. R. Eldridge, Ed. (MITRE Corp., McLean, VA 22101, 1975), p. 265.

2. R. Ramakumar, ibid., p. 279.

G. Cost Schedule

The project cost schedule, based on the latest printout from our Research Office dated Nov. 30, 1977, is given below. I have not yet checked to see if some items which were charged to this Grant should be charged to my current DNR Grant. Any excess of expenditures over budget will, of course, not be charged to DNR.

Category	Amount Spent	Budget
Salary and Wages	$4,815.62	$4,100
Benefits	455.81	291
Travel	21.50	- - -
Communications	17.10	138
Supplies	886.98	1,200
Other Services	- - -	300
Indirect Charges	1,581.44	1,317
TOTAL	$7,778.45	$7,346

The major items in the Supplies category were transistors and other electronic supplies, $495.18 (we managed to burn out several transistors), and two transformers, $185.16.

H. Economic Evaluation

The present synchronous inverter based on a transformer and two transistors gives only 150 watts output before the current waveform begins to distort. This is too low to be of much practical use, so this evaluation will be based on estimated costs for a unit which has maximum output of 600 watts ac for 750 watts dc input, which is near the maximum obtainable from an automotive alternator.

Our present transformer, from Signal Transformer Co., should be able to handle that output without excessive loss. Its price falls from $90 for single units to $50 for 100 or more. Perhaps six transistors would be required. The Motorola 2N6277's presently used cost $30 in small quantities, but Lambda Electronics has recently come out with the PMD 16K 100 100 volt, 225 watt NPN Darlington for $5.60 each, which handles almost the same amount of power as the 2N6277. A Darlington circuit is a power transistor and its associated control transistor; in this unit they are part of the same chip. The estimated production cost for the 600 watt synchronous inverter is:

Transformer	$ 50
6 Transistors	20
Relays	10
Voltage regulator system	10
Capacitor	10
Current control system	10
Meters	10
Chassis, heat sinks, other mechanical parts	20
Assembly labor and other costs	60
TOTAL COST	$200

The synchronous inverter must be evaluated economically in conjunction with a dc wind generating system or other dc source. The lowest-cost assembled 12-foot rotor system described in John Obermeier's thesis (Mechanical Engineering Dept., MSU, 1976) is a Kedco unit rated at 1200 watts and costing $1,695. For a 750 watt unit in quantity production, $500 seems like the lowest reasonable estimate. With $100 installation cost and $200 for the synchronous inverter, the system cost becomes $800. For 20-year life, 8% interest, and 10% salvage value, the prorated annual cost of the system is $74. Wind systems are typically estimated to have a duty factor of 30% because of the intermittent nature of the wind, so the above system rated at 600 watts ac output would have an average output of 180 watts, or 1578 kW-hr per year. This power would need to have a value of 4.7¢ per kW-hr to be economically competitive, based on the above estimated costs and output. This is far above what a utility in Montana would be willing to pay for electricity at present. However, if the system is used by an individual to generate most of his power, with the tie-in to the utility to provide for peak demand and periods of low wind, then the 4.7¢ per kW-hr should be compared with the retail power rate which is only two to three times lower and is rising rapidly. On this basis, such wind systems seem to warrant further development.

III. Conclusions, Recommendations, and Plans for Future Work

A. Conclusions and Recommendations

1. Synchronous inverters show promise of becoming inexpensive enough so that wind systems tied to the utility line by synchronous inverters can be competitive with independent systems using battery storage, especially if the independent systems use ordinary inverters to supply 120 volt, 60 Hz ac appliances.

2. Transistors appear preferable to SCR's (silicon-controlled rectifiers) for use in small synchronous inverters because with transistorized circuits it is easy to put a sinusoidal current waveform into the line, while with SCR circuits of the type used in the Gemini Synchronous Inverter the current waveform can range from spikes to a square wave, neither of which is desirable from the utility's viewpoint because large numbers of such units tied to their line would distort the voltage waveform. Large synchronous inverters used to connect MHD generators, fuel cells, and other dc sources to the utility grid use SCR's, and studies should be made to determine at what minimum power level SCR circuits can provide sinusoidal current to the line and still be economically competitive with transistorized circuits.

3. With presently available power transistors, synchronous inverters employing two transistors in a push-pull arrangement seem to be limited to 150 to 200 watts ac maximum output by the second breakdown phenomenon, and the maximum efficiency is about 70% for a constant dc supply voltage.

4. The efficiency of the two-transistor synchronous inverter could be increases to perhaps the 80 to 85% range by modulating the dc input voltage with 120 Hz in such a way that the peak input voltage occurs

at the current maxima. We were able to modulate the field current to a Delco alternator with the desired modulated waveform, but the magnetization response of the material in the field magnet was too slow to follow this waveform. A different steel, such as employed in transformer cores, would have to be used in the field magnet to make this technique practical.

5. We suggested use of permenent magnet motors as generators to supply the synchronous inverters when we wrote the proposal for this Grant. This now appears impractical because the transistorized synchronous inverter requires a constant voltage, whereas the voltage of a permanent magnet generator is proportional to its speed.

6. Transistors can be paralleled to increase the output of our present synchronous inverter. It also appears feasible to increase both the power and efficiency by connecting the dc source electronically to different transformer taps and transistors at different parts of the ac cycle. The cost of a unit with 600 watts maximum ac output is estimated at $200 in production quantities.

7. Potential users of synchronous inverters often are interested also in being able to obtain 120 volt, 60 Hz ac power in the event of line power failure. Most commercially available non-synchronous electronic inverters put out a square wave voltage unsuitable for some devices and also are not recommended for inductive loads such as motors. Work should be done on a synchronous inverter which in the event of power failure could operate with a 60 Hz oscillator feeding the transistor bases. Such a unit would supply a sinusoidal voltage and current waveform. Provision would have to be made for voltage regulation of the output and for automatic disconnection from the utility line, and batteries would be required for storage.

8. Projected cost per kW-hr for small wind systems with synchronous inverters is roughly five times as great as the present wholesale electric rate, but only two to three times the retail rate to small users. In view of the rapidly increasing cost of electricity and the prospect of power shortages, it appears highly desirable to encourage development and use of small wind systems by individuals, particularly ranchers and country dwellers.

9. Large wind generation systems are expected to provide power at a lower cost per kW-hr than small systems. However, large systems must be cost-competitive relative to other sources of utility power, while small systems owned by individuals need only be competitive relative to the retail rate.

10. The argument has been used that wind-generated power does not reduce the base load requirements for a utility system. This is of course true for a small region, but studies should be made of wind records over a region comprising several states, with hourly correlations of wind velocities at the various stations, to determine the variability of potential windpower available over the region. Also, the potential effect of wind generating capacity on reducing the draw-down required for hydroelectric reservoirs in Montana should be investigated.

11. Our wind generating system including a small synchronous inverter which is located on the roof of the Physics Building at MSU (see Fig. 2) has proven quite reliable under exposure to the temperature and weather conditions there. It has the disadvantages that the aluminum rotor blades are rather expensive, and the belt and chain need fairly frequent attention. Further work should be done on various low and high speed horizontal and vertical axis rotor designs, keeping the objectives of low cost, reliability, safety, efficiency, and esthetics in mind.

B. Plans for Future Work

Under our present DNR Grant we are developing a control circuit for our two-transistor synchronous inverter to match its required power to the power available at various wind speeds. We are also developing the circuit for a transistorized synchronous inverter which will switch from one transformer tap to another at appropriate points in the ac cycle, to improve efficiency and increase output power. These inverters will be tested in conjunction with a wind generator mounted on the back of a pickup to provide controllable relative wind speed. They will then be further tested with two wind generators mounted at our test site west of the MSU campus. One of these generators will be of the ducted rotor type, consisting of fixed vertical plastic sheets supported by a steel framework running between wooden poles to supply enhanced air velocity to a horizontal-axis rotor with fixed orientation. The other system, already constructed, is the downwind rotor type with five flexible blades which will be mounted on an isolated pole. Finally, we will put up two demonstration systems, one in a chinook belt location such as Livingston, and the other in a plains location such as Glasgow. Details of this work will appear in the quarterly and final reports of our present DNR Grant, "Integrated Windpower Systems".

After the above work is completed, we would like to experiment with what we call a delta Savonius rotor, which would have the Savonius S-shape but would taper to a small diameter at the top, so that it could be supported by a single bearing at the bottom. We would also like to develop an inverter which can operate both in the synchronous and independent mode.

IV. Monitoring

The two-transistor synchronous inverter and the flexible-blade downwind rotor developed under this Grant are expected to be studied here and not at any demonstration site. Reports on their performance will be made in connection with our current DNR Grant, "Integrated Windpower Systems". Their performance will continue to be monitored during the remainder of the five-year period, unless they are superceded by improved designs.

V. Public Availability

The above inverter and rotor will probably be at our test site just west of the MSU campus beginning this spring. Anyone wishing to see them should contact me by telephone or letter. Boots would be advisable for visiting the site in winter.

Over the past years I have shown the wind energy project to about one person or group per month. Most are from the Bozeman area, others from various parts of Montana, and a few from out of state. Those who are interested in putting up their own systems often find the work too difficult, and in many cases they are interested in an independent system, or in a system with the capability of operating independent of the utility grid.

VI. Program Evaluation

I have enjoyed working under the Renewable Energy Program because the DNR personnel have been helpful, have kept paperwork to a minimum, and show interest with occasional visits without trying to tell me how to do the work. I only wish that Federal granting agencies would be so cooperative. I consider this an important program, am proud that Montana has it, and hope it can be continued.

<table>
<tr><th colspan="6">AC phase angle</th><th>Total loss</th><th>Power out</th><th>Power in</th><th>Effic., %</th></tr>
<tr><th>0°</th><th>15°</th><th>30°</th><th>45°</th><th>60°</th><th>75° 90°</th><th></th><th></th><th></th><th></th></tr>
<tr><td colspan="6">0.215</td><td>0.215</td><td>0.785</td><td>1.000</td><td>78.5</td></tr>
<tr><td colspan="2">0.022</td><td colspan="4">0.126</td><td>0.148</td><td>"</td><td>0.933</td><td>84.2</td></tr>
<tr><td colspan="3">0.064</td><td colspan="3">0.065</td><td>0.129</td><td>"</td><td>0.914</td><td>85.9</td></tr>
<tr><td colspan="2">0.021</td><td colspan="2">0.055</td><td colspan="2">0.023</td><td>0.099</td><td>"</td><td>0.884</td><td>88.8</td></tr>
<tr><td colspan="2">0.021</td><td>0.015</td><td>0.014</td><td colspan="2">0.023</td><td>0.073</td><td>"</td><td>0.858</td><td>91.5</td></tr>
</table>

Table I. Relative power losses and efficiency for idealized synchronous inverter for various switching cycles. The idealizations consist in assuming that the collector-emitter voltage V_{CE} of a transistor can be allowed to drop to zero before switching that transistor out of operation, and that the product of the collector current I_C with V_{CE} is the only power loss in the circuit. For all five switching cycles shown above, the transistor attached to the end of the primary coil is switched on at 0° phase, corresponding to ac line voltage crossing zero. For the last four switching cycles, switching to other transistors connected to taps successively closer to the primary center tap occurs at 30°, 45°, and/or 60° phase, as indicated by vertical bars. Values between bars indicate relative power losses for those portions of the cycle. The operation is symmetric about 90° phase, and no switching occurs at 90°. Efficiencies of the 2nd, 4th, and 5th switching cycles (which correspond respectively to circuits with 2, 3, and 4 pairs of power transistors in a push-pull circuit) could be improved by changing the switching angles.

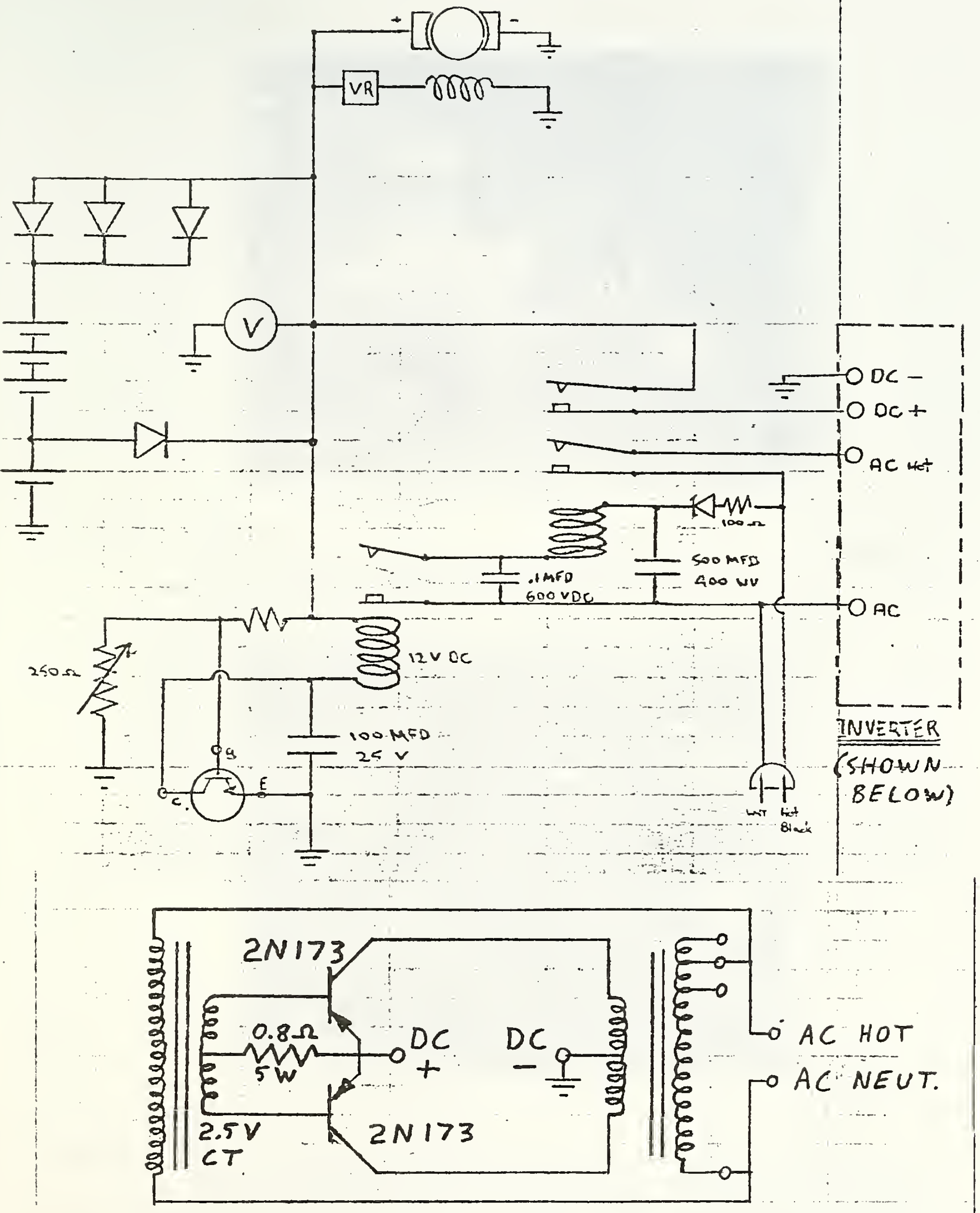


Fig. 1. 60-watt synchronous inverter with interlock relays, and batteries serving as auxiliary load and field excitation source.

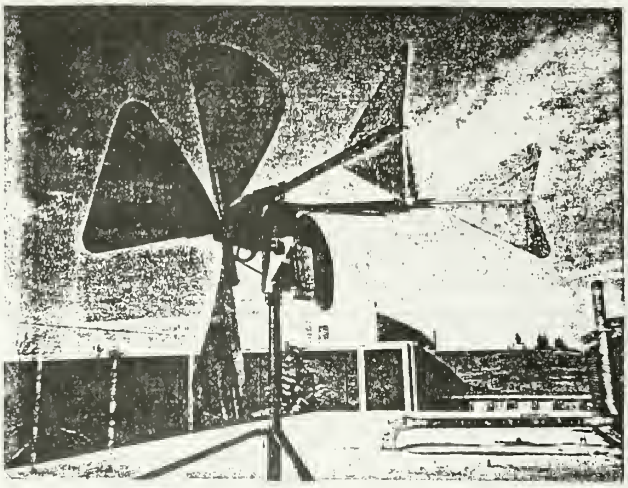


Fig. 2. Wind generator system located on roof of Physics Building at Montana State University. The 8-foot diameter rotor is made of 0.140-inch 7075-T6 aluminum sheet rolled to a 4-foot radius attached to a steel hub mounted on a Buick front hub. Trail cycle sprockets and chain transmit power to an idler from which a pulley and V-belt drive runs the Delco automotive alternator. A voltage regulator maintains 14 volts output, and a brush and slip ring bring the dc power to the support post. A friction bearing at the top of the support post allows the assembly to fact the wind. The split tail fin linkage is arranged so that a strong wind can overcome a spring force and push the two tailfins together while at the same time the rotor is turned sideways to the wind to avoid overspeed.

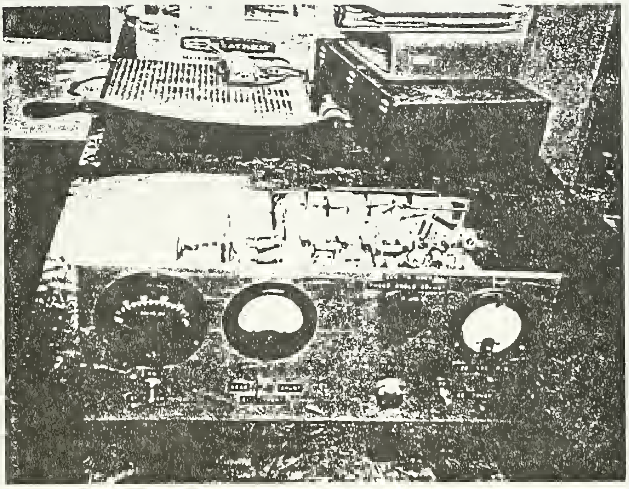


Fig. 3. SCR-type synchronous inverter. The SCR's (silicon-controlled rectifiers) are mounted at the right rear.

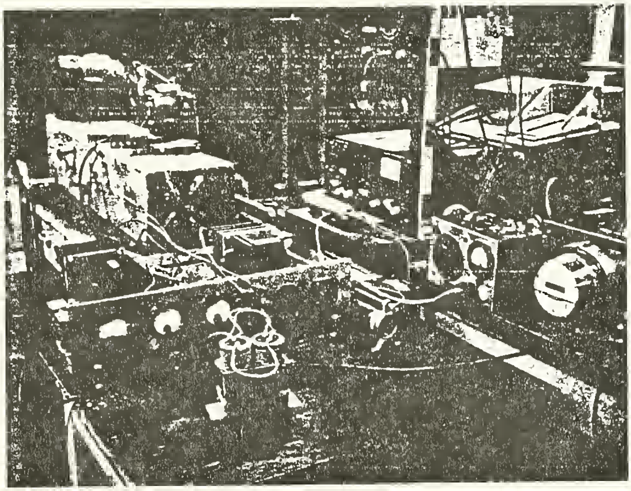


Fig. 4. Transistorized synchronous inverter (left front), with front panel meters for dc input voltage and current, dc current to voltage regulator and field, and ac output voltage and current. The output transformer is at left, and the input transformer for base bias at right. Transistor heat sinks are just behind the transformers. Capacitors to smooth the dc input voltage are in front. The dc power for bench tests is provided by the Delco alternator driven by an ac motor, both mounted on the beam in upper left. To the right are the Variac used to control the base drive and thus the output power, and a watt-hour meter to measure the power fed into the ac line.

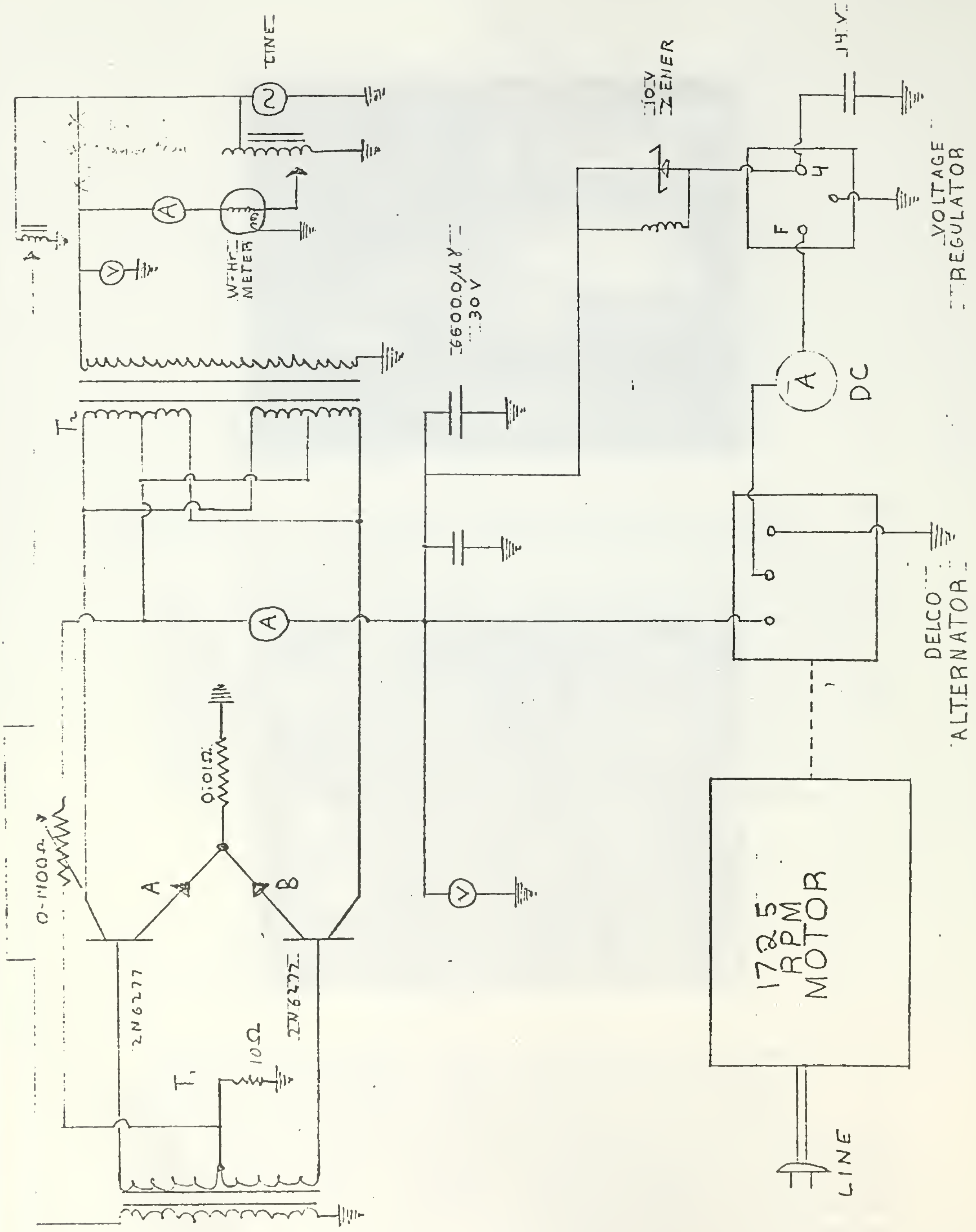


Fig. 5. Present transistorized synchronous inverter circuit and associated bench test apparatus.

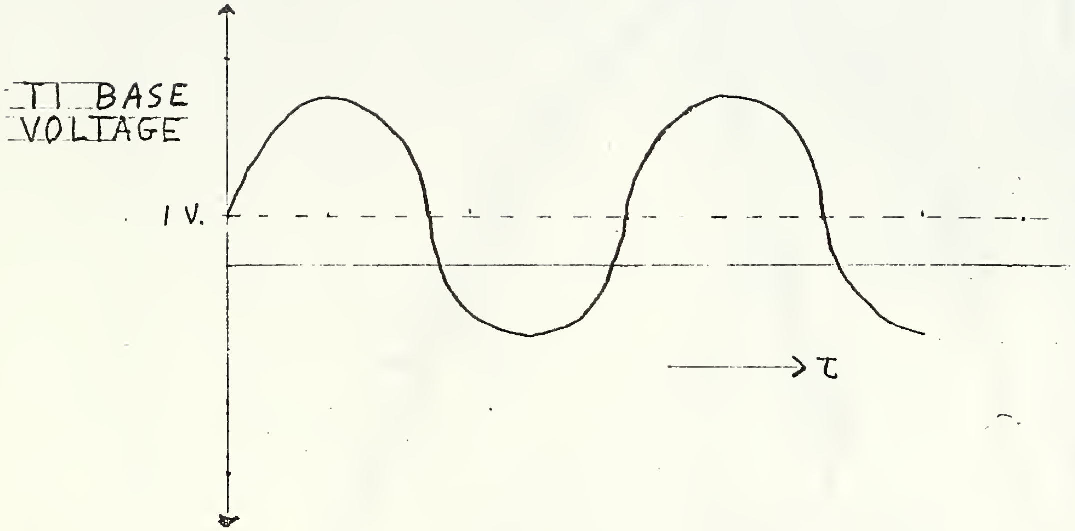


Fig. 6. Voltage waveform at base of transistor in synchronous inverter.

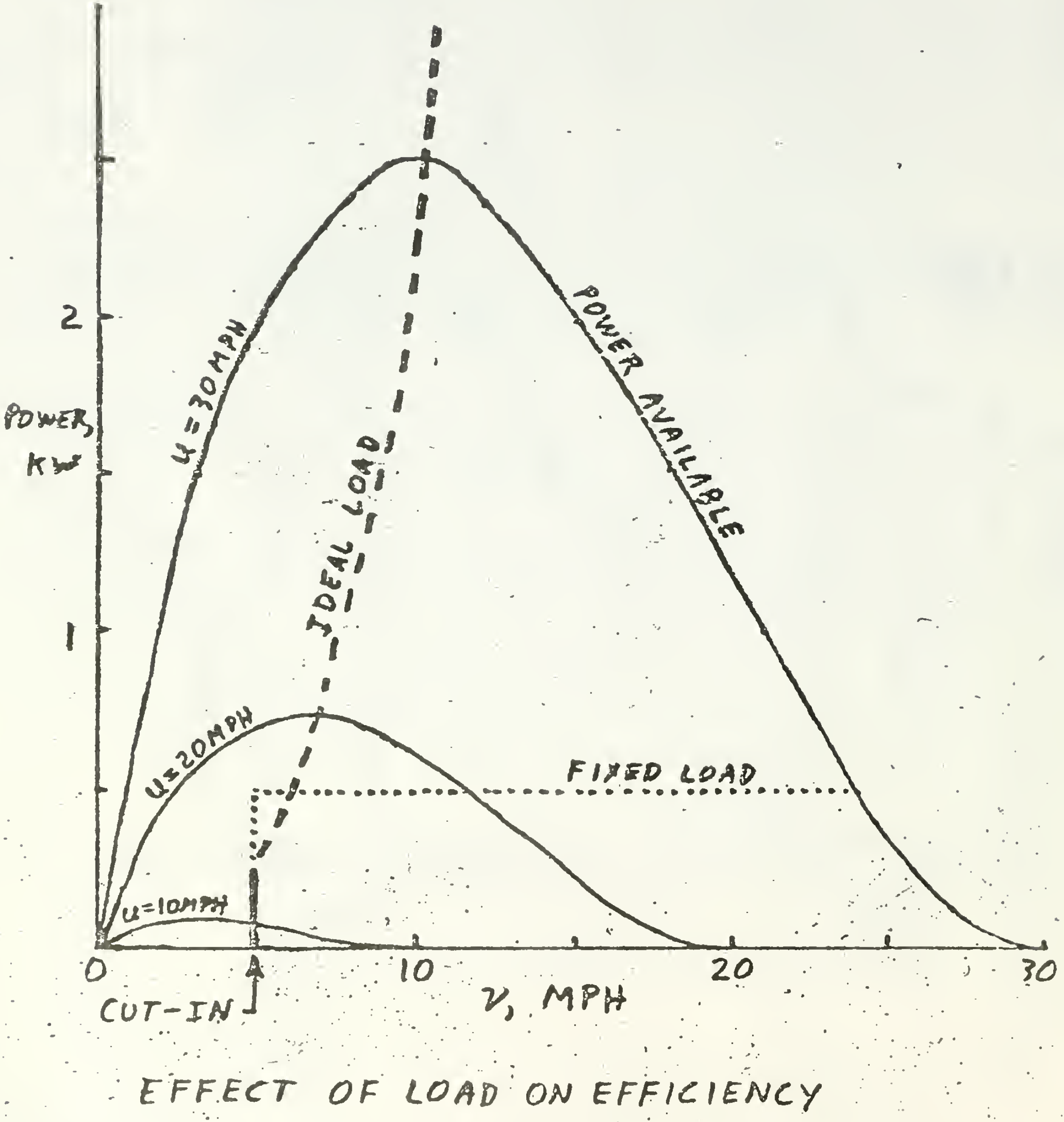


Fig. 7. Theoretical power available from the wind (based on theoretical maximum of 16/27 of kinetic energy of undisturbed wind passing through area equal to rotor swept area) for a 6-foot diameter rotor, as a function of normalized rotor speed v, where v is the speed of the rotor at a radius R_v at which the rotor speed is equal to the wind speed u for an unloaded (free-wheeling) rotor. The ideal load (dashed) will vary as the cube of rotor speed v.

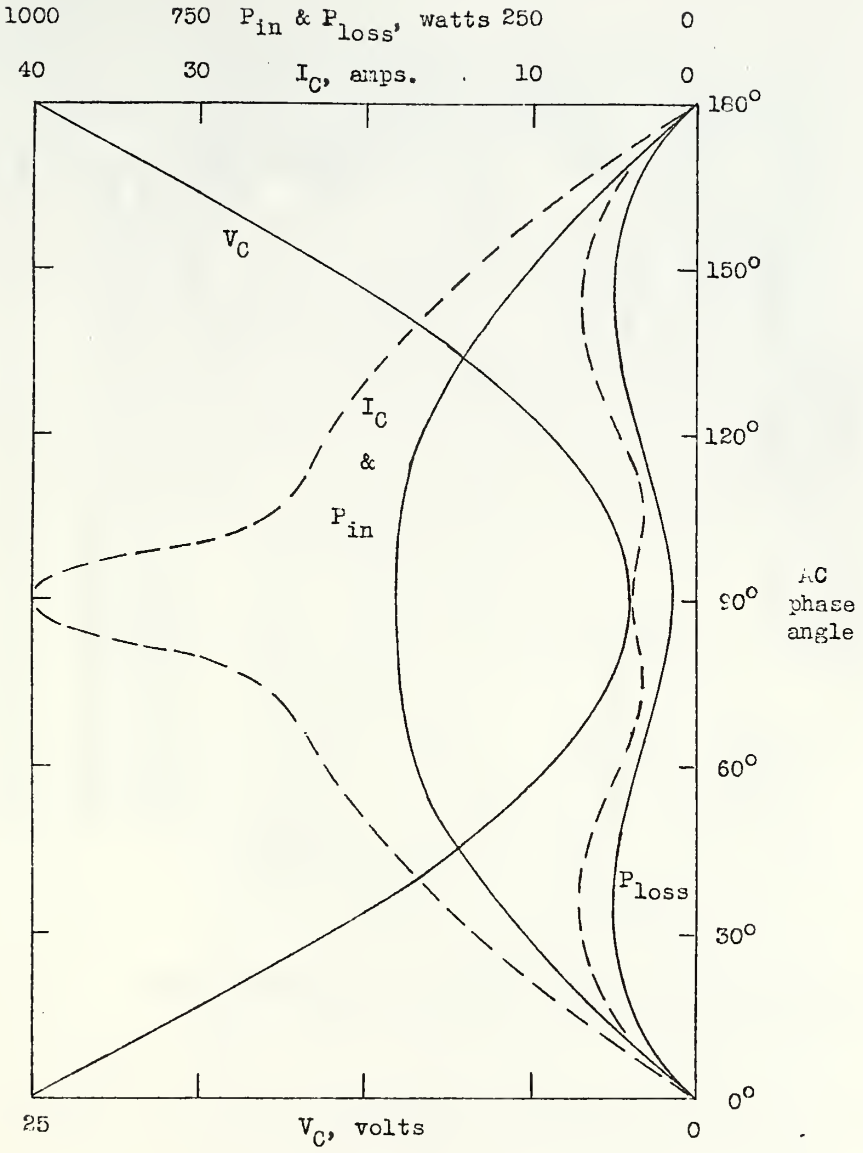


Fig. 8. Waveforms for present transistorized synchronous inverter, for 150 watts (solid) and 200 watts (dashed) ac output power. The dc supply voltage is 25 volts. The collector voltage V_C is shown the same for both power levels, thus ignoring slight differences due to transformer losses. The collector current I_C is a slightly flattened sine wave for 150 watts output, but develops a pronounced spike at 200 watts output because of second breakdown in the transistor. The input power is the product of I_C and the 25-volt supply voltage. The power loss to heat in the transistor and in the emitter resistor is $V_C I_C$.

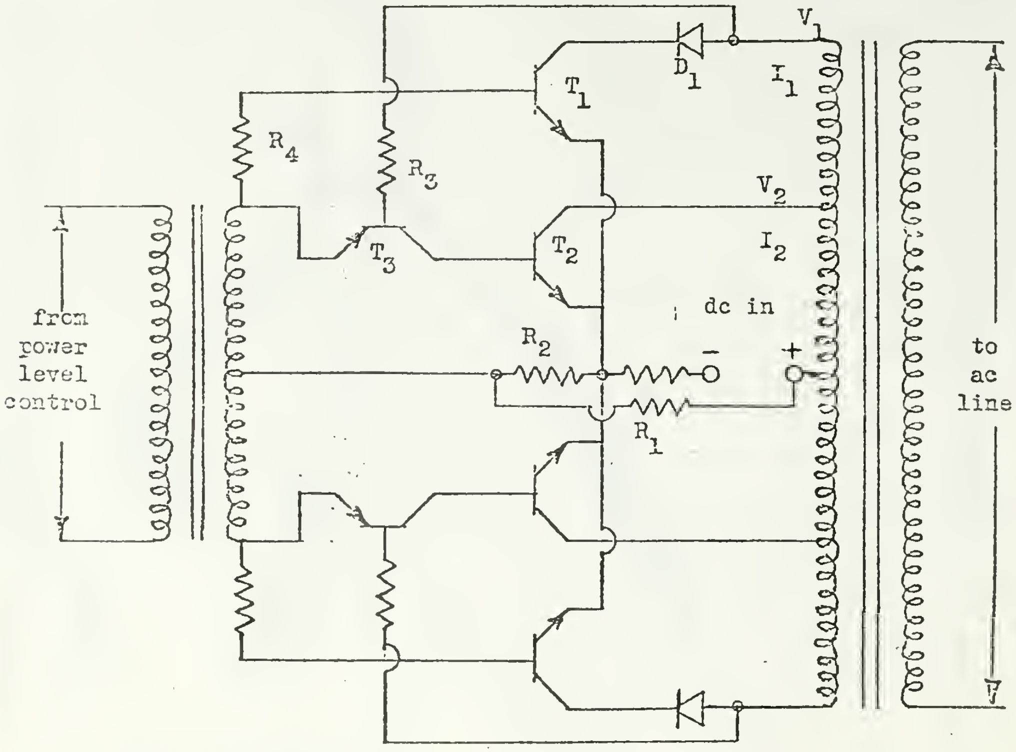


Fig. 9. Proposed transistorized synchronous inverter circuit.

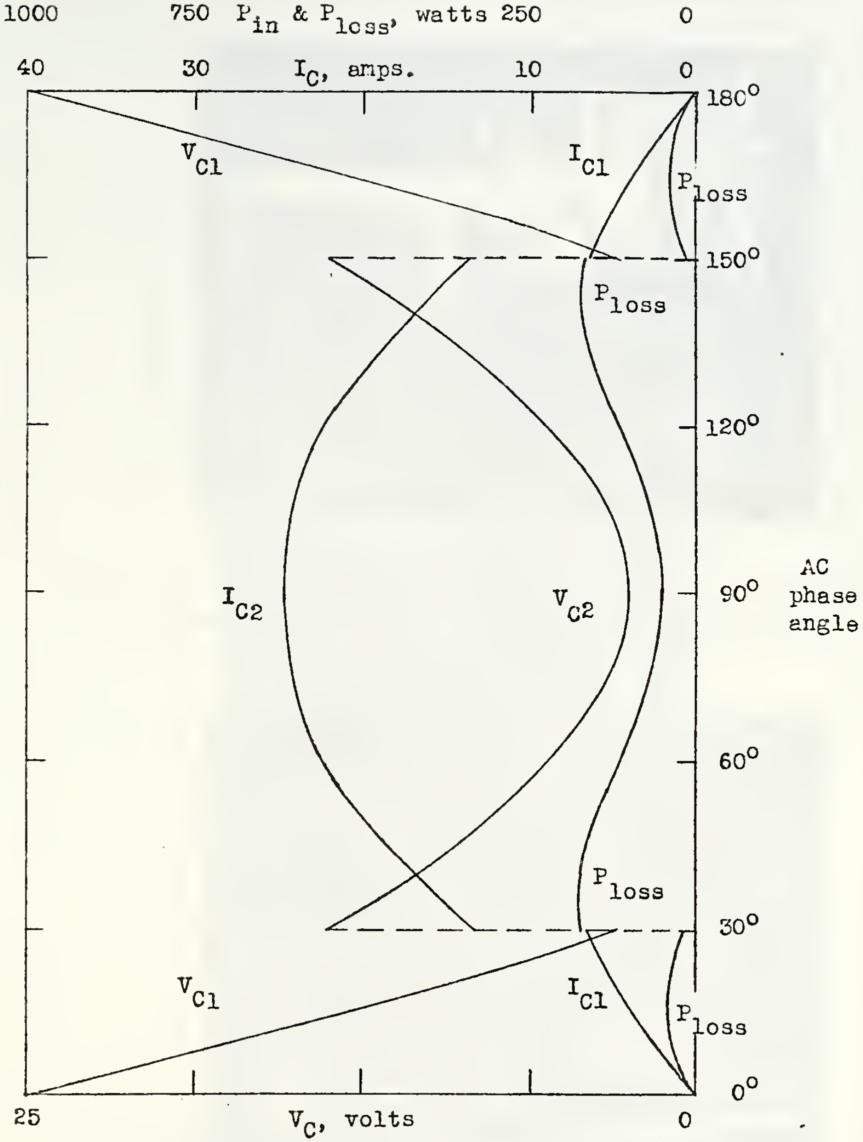


Fig. 10. Expected waveforms for proposed transistorized synchronous inverter operating at 200 watts ac output power. Compare with Fig. 8 for present inverter results drawn to the same scale. Note that power loss is considerably less during the 0-30° and 150-180° portions of the cycle, and that pips due to second breakdown shown in Fig. 8 are not expected to occur because transistor T_2 is unloaded until 30° phase angle. The switching angles of 30° and 150° are dictated by our present transformer, which has turns ratios giving relative primary voltages of 2, 1, 0 (CT), -1, -2. Lower losses would occur for switching angles of 45° and 135° (3rd switching cycle, Table 1), requiring a transformer with relative voltages of 2, $2^{\frac{1}{2}}$, 0 (CT), $-2^{\frac{1}{2}}$, -2.

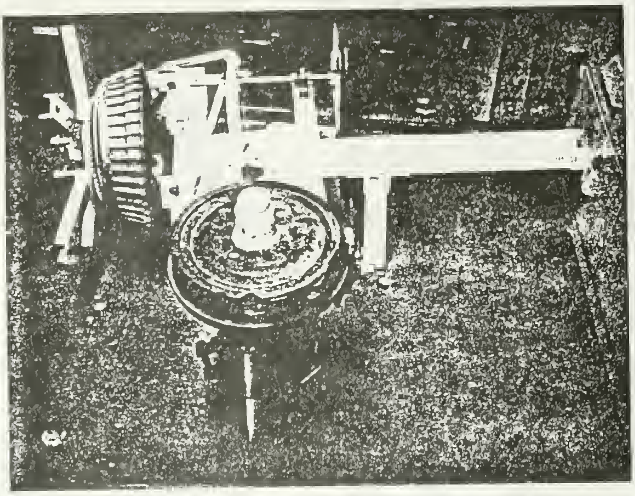


Fig. 11. Vertical axis rotation hub (front), wind rotor hub (left), and mainframe (top center) for flexible-blade downwind rotor wind generator system.

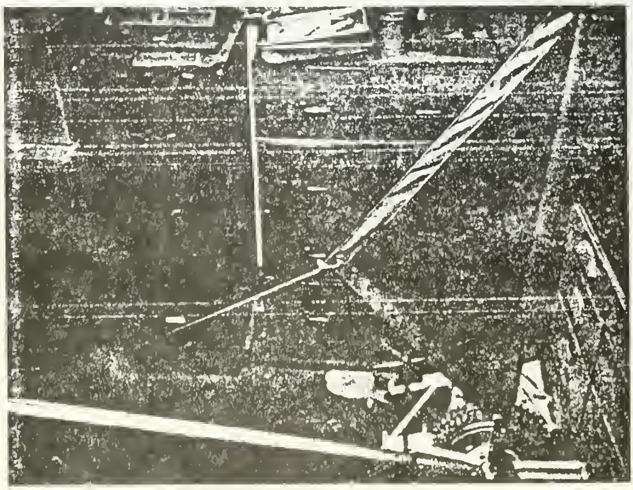


Fig. 12. Wind rotor hub with two spars and attached flexible Neoprene blades, showing cable attaching one blade to neighboring spar, for above wind generator system.

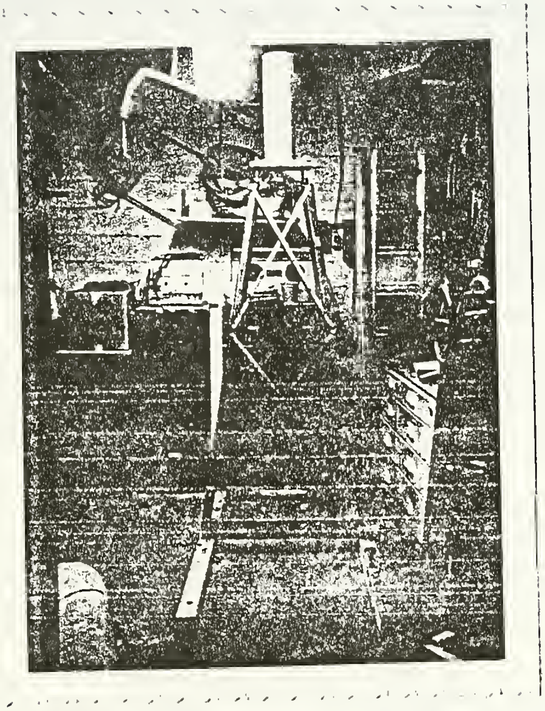


Fig. 13. Windmill mounting tower for testing wind generator system on pickup truck to obtain controlled airspeed.

I. OBJECTIVE

The main purpose of this work was the development of small, economically competitive systems to generate electricity from windpower. Widespread use of such windpower systems would conserve fossil fuels, reduce pollution from burning of such fuels, reduce dependence on nuclear plants with the associated safety and spent fuel storage problems, and help maintain the heat balance of the earth.

A subsidiary goal of this work was the development of windpower systems which can also serve as agricultural shelterbelts, which would increase crop yield by enhancing snow retention, retarding evaporation, and reducing wind erosion of topsoil.

The first objective of our proposed work was continuation of development of synchronous inverters. Such inverters are necessary to integrate the windpower systems, or eventually solar electric generations systems, into the electrical grid. The alternatives are use of induction or synchronous generators which require constant-speed operation, or variable-speed fixed frequency generators which need complex control electronics. Another option is independent system operation, which requires storage of energy in batteries or by other means, which is expensive at present, or else the use of the power for heating in applications where continuity of power is not required.

The second objective was the development of ducted windmill power generation systems, with fixed barriers acting as ducts to increase the air velocity at the wind rotors. These barriers if arranged in rows would serve as effective shelterbelts, even at high wind speeds for which the wind rotors would be ineffective for absorbing energy.

The third objective was the installation of two systems similar to the system presently being tested here, to determine their performance under conditions of higher average wind, and to demonstrate their reliability. Installation of these systems was planned for two locations, one which is subject to extremely strong winds such as Livingston or Cut Bank, and the other more typical of the open plains such as Glasgow or Sidney.

II. PROJECT IMPLEMENTATION

INTRODUCTION

This report describes work done under the Montana Department of Natural Resources and Conservation Alternate Energy Grant, "Integrated Windpower Systems", from September, 1977 through July, 1979. This work is a continuation of research and development done under a previous DNRC Grant, and of still earlier work dating back to 1973 which was unsupported except for summer salaries for students supplied by a National Science Foundation Undergraduate Research Participation grant and supplies and space provided by the Montana State University Physics Department.

In a related grant project from DNRC, we are to bench test a 5-kilowatt inverter manufactured by the Real Gas and Electric Co., in Santa Rosa, CA which can operate either in the synchronous or independent mode. This work is scheduled for completion in December, 1980.

Our work described in this report deals with small wind-electric systems which are integrated into the utility grid. First the three different types of wind rotors and alternator drive trains dealt with in this work are described. Next discussed are our various methods of providing for vertical axis rotation to allow the rotor to align with the wind while at the same time providing for electrical connections between the alternator on its pivoting platform and the fixed support post.

Following this is an explanation of our synchronous inverters which convert direct current to alternating current synchronized with the utility line. Next comes a description of our bench test apparatus and test results for our synchronous inverters. Field tests of the entire systems are then summarized, followed by a description of other types of wind systems. These include systems with induction motors acting as induction generators (a concept we tested briefly), the proposed vortex system which we analyzed, and the Oklahoma State University system with bicycle-wheel-like rotor and variable-speed, constant-frequency alternator which we observed. Finally, system cost and economics are considered.

This report provides a quite detailed account of our work, but additional details and photographs can be found in the four Quarterly Reports.

Wind Rotors and Generator Drive Trains

We have built three different wind rotors and associated drives, which we have tested with our synchronous inverters. The first, built before our DNRC projects began, has an 8-foot-diameter rotor with four aluminum blades and a split tailfin for overspeed control. It is shown in Figs. 1 and 2. It has been generating power on top of the MSU Physics Building since 1974, and has put power back into the line by means of a synchronous inverter since 1975. The second system, shown in Fig. 3, has a 10-foot-diameter downwind rotor with five sailblades attached to aluminum spars. Its construction was completed during this Grant period, and it was installed at our test site near the MSU Veterinary Research Laboratory. The third system, built from a kit purchased from Krueger Engineering Co., has a 7-foot-diameter rotor with three wooden blades of airfoil cross-section. It was constructed during this Grant period and mounted as seen in Figs. 4 - 6 in the throat of the Venturi-shaped duct at our local test site. Detailed descriptions of these three systems follow.

During 1974 we built the system shown in Fig. 1, which has four blades of 0.140-inch 7075-T6 aluminum blades giving an 8-foot diameter rotor. The blades were rolled into a cylindrical form with 4-foot bend radius to provide increased strength and to reduce the mean pitch near the blade tips. The blades are reinforced by a second plate of the same material rivited on near the roots. The blades are attached by U-bolts to four steel pipes extending out from a welded steel hub. This steel hub is bolted to a Buick front hub from a junkyard, which provided a strong and low-cost bearing. A trail cycle sprocket on this hub transmits power by a chain to the idler shaft. From the idler shaft the power was transmitted to a Delco automotive alternator by a fan belt.

The whole arrangement can rotate to face the wind by means of a friction bearing on the vertical steel support post, and power is brought out by means of a brush contacting a slip ring attached to the post. In Fig. 2 the split tailfin mechanism can be seen. The two fins are held apart by a spring, but a strong wind can overcome the spring force and push the two tailfins together. The linkage is such that the rotor is turned sideways to the wind when the tailfins move together, thus protecting the rotor from excessive rotational speed. Also visible in Fig. 2 is the support post, which is attached to the railing on top of the Physics Building on the MSU campus.

This system has been in continuous operation since July, 1974, and has been used in conjunction with the synchronous inverter since July, 1975. The batteries are still necessary to absorb part of the power, because this inverter can only absorb 100 watts, while the alternator (which incorporates a rectifier in its housing) can produce over 400 watts. The system has been quite reliable, except for minor problems which were corrected by strengthening the tailfin stop, redesigning the brush and slipring, and using a wider V-belt.

Some rough efficiency tests were run by comparing the electrical output with the wind energy available as measured by the anemometer. Based on an available wind energy of 16/27 of the kinetic energy of wind passing through a circle of the windmill diameter at the speed measured by the anemometer, an efficiency of about 30% at a wind speed of 18mph was measured. Bench tests of a similar alternator gave a maximum alternator efficiency of 46%. Accordingly, the rotor and drive train efficiency comes out to 65%, somewhat higher than would be expected for a rotor of this type.

Our second wind rotor was constructed with flexible blades made of Neoprene, as shown in Fig. 3. Each blade is attached to a 5-foot-long aluminum tube spar. The five spars are attached to an automotive front hub. Originally, a light steel cable attached to the eye at the tip of each triangular blade ran over a pulley at the tip of the adjacent spar, then inside that spar to a spring attached to the base of the spar. The function of the spring, which has a certain preload force required to begin stretching it, was to allow the blade to feather in a high wind. The rotor hub is attached by a bracket to another vertical-axis automotive hub to allow the wind rotor to change direction to face downwind. The spars, instead of extending radially outward, lean downwind by the "coning angle" of 7 degrees which has been found necessary by other builders of downwind rotor systems in order to provide stability. The alternator drive of this flexible-blade system resembles that used in our original fixed-blade system. This system was installed on top of a 15-foot pole at our test site 1/4 mile west of the MSU Veterinary Research Laboratory. The wind averages about 7 mph there, as compared to 4 mph on top of the Math-Physics Building.

During the summer of 1978, the V-belt and pulleys for this system were replaced by 3/8-inch pitch, 3/4-inch wide toothed pulleys and belt. These cost about $40 as opposed to about $15 for a V-belt and pulley (the alternator originally has a V-pulley), but seems to be worth the cost because of reduced friction. Specifically, with the V-belt the rotor started to turn in 7 mph winds, put out 300 watts to a resistive load, and survived an estimated 40 mph wind while free-wheeling. With the toothed belt (timing belt) instead of the V-belt it now starts in a 4 mph wind, indicating that friction has been reduced by a $(4/7)^2$ factor. The system received a good test from the wind of Nov. 4, 1978 which averaged 26 mph during a typical 15 minute period and gusted to perhaps 40 mph. With the voltage regulator in series with a Zener diode for 22-volt dc output, the system cut in at about an 18 mph wind, while without the Zener for 13-volt operation only a 9 mph wind was needed for cut-in. At an average 26 mph wind with the controls set for 100 watts ac output (200 watts dc input) the inverter was operating most of the time. This power did not seem to load the rotor excessively. The springs allowing the blades to feather were in operation much of the time. Perhaps a higher tension in these springs would allow higher speed and higher efficiency operation of the rotor. Also, the speed ratio of the alternator relative to the rotor is only 20:1 (60:14 sprocket tooth ratio and 84:18 pulley tooth ratio). A higher ratio would reduce the cut-in wind speed, especially now that friction has been reduced by using the timing belt.

In November, 1968, this rotor failed because one of the five cables running from the apex of a sail to the tip of the adjacent spar broke where it ran over a pulley at the tip of the spar. The cable ran over the pulley to a spring near the base of the spar which, during periods of high wind, stretched and increased the pitch angle of the sail, preventing overspeed. The cable broke because the pulley diameter was too small. Rather than redesign the system with a larger pulley, I decided to see if the rotor could do without overspeed protection, so I redesigned the cable to attach to the tip of the adjacent spar. The system thus rebuilt operated with the inverter as load from late February until late April, and without load (worst case for overspeed) since then, and although occasional high winds have come up, the system has not been damaged.

We built our third system from a kit purchased from Krueger Engineering in Manvel, ND. The complete system with 7-foot diameter rotor and Delco 55-ampere alternator costs $185. The rotor consists of pine boards glued together, then sanded to shape as indicated on templates for various distances from the hub. A student assembled the rotor in 100 hours, but estimates that the next one would take him 30 hours. The kit includes a tailfin and provision for vertical axis rotation by means of an automotive hub just behind the rotor. This hub has slip rings mounted inside it, on a modified backing plate. This is by far the lowest-cost system for its size to appear on the market. For this reason, I considered it worthwhile to test this system along with the downwind sailblade rotor and our original 8-foot diameter aluminum blade rotor.

This rotor operates at much higher rotational speed than our other two, and consequently this system requires only a one-step speed increase to the alternator, achieved with V-belt and pulleys.

It has held up quite well since being installed in April, 1979, but there is a small amount of cracking of the fiberglass coat over the rotor. Also, the setscrews holding the rotor onto its 1-inch diameter shaft work loose; a key and keyway arrangement would be better.

Provision for Alignment with Wind and Associated Electrical Connections

Either an upwind or downwind rotor must be perpendicular to the wind for best efficiency. To achieve this alignment for our aluminum-blade rotor, we used a split-tailfin arrangement and vertical-axis friction bearing as described above. The Krueger system has a tailfin and vertical-axis automotive type bearing with slip rings and brushes for electrical contact, but we didn't use these provisions because we mounted this rotor in the throat of our Venturi duct in a fixed orientation.

Several alignment and electrical connection arrangements were tested with our sailblade rotor system. This system is mounted on a Rambler front hub to provide vertical axis rotation so that the rotor can face downwind. Originally a copper strap around the periphery of the brake drum served as a slip ring, and was insulated from the drum by a strip of rubber. Power was brought out by means of a stationary carbon brush held against the copper strap by a spring. This system wasn't adequate for use with our inverter when the power level control was added, because three connections (besides a ground connection through the bearing) had to be made to the rotating rotor platform.

We then provided a flexible cable to make these four connections, and for about two months we bolted down the mounting platform so it couldn't rotate about the vertical axis. It became evident that the wind direction here is too variable for the economy of dispensing with vertical axis rotation to compensate for the resulting loss in energy output. (For random wind direction, fixing the rotor direction reduces the energy output to 42% of that for the free rotor, for a sail-blade rotor which operates equally well facing upwind or downwind.) We then allowed vertical axis rotation but provided a stop so that the cable bringing the four leads to the inverter in the control trailer wouldn't get twisted.

This stop prevents vertical axis rotation through more than 360°. This system has worked reasonably well, but has two drawbacks. The stop must be designed to absorb quite a bit of energy in strong winds, and the sudden stops may eventually damage the system. Also, occasionally a steady wind pushes the rotor mount assembly against the stop with the rotor sideways to the wind, so a day or more of potential power production is lost.

An improved system has been designed and built, but not yet tested. It has a variable-torque stop so that a strong wind can overcome the restoring torque and push the rotor into an orientation almost perpendicular to the wind, but as soon as the wind lets up for a moment the restoring torque will bring the rotor back toward its equilibrium orientation.

Our vertical axis rotation mount has a frame of four square steel tubes welded to top and bottom plates, as shown in Fig. 7. The bottom plate will attach to the fixed tower or windmill mounting post, while the top plate contains the main vertical axis bearing. A few inches down from the top is a plate holding a guide bearing which serves to prevent excessive twist on the main bearing. A hollow one-inch shaft runs through both bearings, and the wind rotor mounting bracket can rotate to face the wind. At the lower end of the shaft, below the guide bearing, is attached a standard circular electrical junction box plate with three cable clamps mounted in knock-out holes as shown in Fig. 7. A similar junction box plate is attached to the (fixed) bottom plate of the rotation mount. Five additional plates are located with equal spacing between the top and bottom plate, held in position by Tygon tubing clamped in the outer two holes of each plate. The electrical cable to the alternator is clamped in the center holes of the plates. As the rotor bracket rotates through an angle θ to face the wind, the successive plates going from top to bottom rotate through angles θ, $5\theta/6$, $2\theta/3$, $\theta/2$, $\theta/3$, $\theta/6$, and 0. For $\theta=0$ the Tygon tubing is unstretched, and it stretches by an amount proportional to θ^2 for small angles. The restoring torque is provided by the horizontal component of the force on the stretched Tygon tubing, which is proportionally to θ times the total force for small angles. Accordingly, the restoring torque is proportional to θ^3, so that it can be very weak for θ between -180° and 180° (allowing almost unhindered ability to face wind from any direction), but rises rapidly if the wind tries to push the rotor orientation more than 180° away from equilibrium.

If Tygon tubing turns out to be unsuitable, it could be replaced by tension springs. Also, the tubing or springs when stretched would increase the vertical load on the bearing, but the system could be redesigned to push upward on the rotor mounting bracket and thus decrease the vertical bearing load as the tubes or springs are stretched.

Another possible application for this type of vertical rotation mount would be with hydraulic drive wind generators, for which the wind rotor turns a low-speed hydraulic pump, while the generator is located in a convenient fixed position at ground level and is turned by a high-speed hydraulic motor. This system requires that two hydraulic lines run to the rotating platform. If rotation of the platform is unlimited, an expensive leakproof coupling must be provided. Our mount design would obviate the need for such a coupling if flexible hydraulic hose is run through the center holes of the plates.

Synchronous Inverters

The wind systems as described thus far, each with its wind rotor, generator drive train, generator, and provision for bringing power from the pivoting rotor platform down to the ground, are complete for purposes of producing 12-volt dc power for charging batteries, operating resistance heaters, or other suitable applications for dc power. If 120-volt, 60 Hz ac power independent of the utility line is desired, an inverter must be used in addition, as well as a battery bank to store energy during periods of low wind. Relatively inexpensive inverters producing a square wave 60 Hz output are commercially available.

If utility power is available, wind energy can be used to supplement this power in an integrated system if a synchronous inverter is used. An expensive battery bank is not needed for this system. Two synchronous inverters are commercially available. One is the 8 kilowatt Gemini model, produced by Windworks in Mukwanago, Wisconsin, which employs SCR's (silicon controlled rectifiers) which produce a rather spiky, non-sinusoidal current waveform. The other is a 5 kilowatt synchronous/independent inverter produced by Real Gas and Electric Co. of Santa Rosa, California which is claimed to produce a good sinusoidal current waveform in the synchronous mode. It has the advantage of being able to operate also in the independent mode, but it is quite expensive. I have a DNRC Grant to bench test this unit in autumn, 1980, after returning from sabbatical leave.

Our work has been in developing smaller synchronous inverters than the above units. We describe here the basic circuit and our various actual and proposed modifications for improving its reliability and efficiency. The basic inverter circuit is quite simple, and could consist of only four circuit elements: An output transformer to feed synchronized ac power into the line, two transistors in push-pull to feed dc current from the wind generator into the output transformer, and an input transformer connected to the line to control the transistor currents in synchronism with the line.

The direct current (dc) is directed by the transistors to flow first one way, then the other way, in the centertapped primary of the output transformer. This produces an alternating magnetic field in the transformer core, producing a current in the secondary which is fed into the alternating current (ac) line. The transistors are controlled to reverse the current in the output transformer by means of the input transformer which provides a synchronous signal from the line to the transistor bases. The power fed into the line can be measured by noting the rate at which an ordinary utility watt-hour-meter, connected between the synchronous inverter and the ac line, runs backwards. This type of circuit produces a sinusoidal current waveform which is pleasing to the utility company.

One disadvantage of this simple synchronous inverter circuit is that it has constant input and output power, while the windpower available varies as the cube of the wind speed. To obtain an inverter power level which varies approximately as this cube function, we use a signal from the Delco alternator "R" terminal which has frequency proportional to alternator rpm to control the current level in the power transistors. With the inverter loading the alternator and eventually the wind rotor in this way, the rotor rpm is kept near the value required for maximum efficiency as wind speed varies. Schematics and explanations of our inverter circuit with this type of power level control appear in Appendix A.

The voltage regulator circuit shown in Appendix A is based on an automotive "12-volt" regulator, but the circuit is modified to allow operation at higher voltage. The modification consists in putting a Zener diode between the dc source (Delco alternator with built-in diodes) and the automotive voltage regulator. The alternator output voltage then is the regulator voltage plus the Zener breakdown voltage. A resistor must parallel the Zener diode to provide a current path to the regulator and field during voltage build-up.

The reason for operating at higher dc voltage is that the alternator reaches peak efficiency of about 65% when operating at 30 volts and producing 30 amperes. When operating at 14 volts as controlled by the regulator alone, it achieves maximum efficiency of about 45% for a current near 40 amperes. Also, power losses in the inverter power transistors are lower compared to their output power when they operate at higher voltage. A disadvantage of higher dc voltage is that higher rpm is required before the alternator will cut in.

In our Final Report on our previous Grant, "Synchronous Inverter Development, we proposed a circuit which would switch from one transistor to another transistor connected to a different output transformer tap, as described in Table I, Figs. 9 and 10, and associated text of that Final Report. The aim was to increase the efficiency by reducing the power lost to heat in the transistors. We constructed a circuit of this type and achieved a maximum efficiency of about 60%, similar to that of our original simpler design which switches transistors only at the ac zero voltage crossing points. Also, the waveform of the current into the ac line had several spikes which do not occur for our original circuit. Perhaps this approach could provide better efficiency and acceptable waveform eventually, but in view of limited time and resources we decided to abandon this approach. These tests were run on our 5th inverter, which we call S I-5. A photograph of this inverter appears in Fig. 8.

We ran some brief tests on the other inverter (SI-4) which showed that this circuit can operate in the independent as well as synchronous mode. The 125-volt winding of the transformer was disconnected from the ac line and connected to a 200-watt, 125-volt light bulb. The bases of the power Darlington transistors were still connected to 60 Hz ac signals derived from the line, the two base signals being 180° out of phase. Of course, in true independent operation these base signals would have to be derived from an oscillator instead of the line. The important point is that our push-pull transistor-transformer circuit is capable of operating in both the synchronous and independent modes.

We have solved the problem of protecting our circuit from switching transients. These transients didn't occur in bench tests in which the ac voltage was raised gradually be means of a Variac. In field operation, the ac voltage is applied instantaneously by means of a relay, as shown in Fig. 9. This relay coil is ac-operated, but cannot be actuated until the dc relay closes. The dc relay closes whenever the dc voltage is above 18 volts. Accordingly, the ac relay is closed only when full dc voltage is available for proper circuit operation and the ac line is live also.

These protective measures were used with the SI-5 inverter, and appear in the circuit in Fig. 9. This circuit has two power transistors in parallel in each half of the push-pull circuit. To equalize the current to each transistor in each pair, 0.05 ohm resistors are placed in the emitter leads. The transistors were also matched as closely as possible by pretesting them on a transistor curve tracer.

The circuit in Fig. 9 has base drive supplied by a transformer, and has power level and base bias control potentiometers. Normally a power level control unit would be used, which varies the power level in response to changes in alternator rpm, to match the load constituted by the inverter to the power available from the wind. The level control wasn't working at that time, so this fixed-power-level circuit was used in the interim. (The power level control has since been debugged, and has worked properly both in bench and field tests.)

Another improvement over the circuit shown in Appendix A is the addition of a field tickler circuit, which appears in Fig. 9. This circuit is helpful in beginning the excitation process of the Delco alternator. This alternator, whose circuit appears in Appendix A, has internal diodes to convert the 3-phase ac it generates to dc. These diodes have very high resistance for voltages below half a volt, and this high resistance impedes the voltage build-up process. In the SI-1 unit on top of the MSU Physics Building, a 2-volt battery with a forward-biased diode is used to tickle the field with a voltage above this alternator diode forward drop obstacle. Once the voltage builds up, the diode in series with the battery prevents current from the alternator from flowing back through the battery. Replacing this battery periodically is a nuisance, so in the SI-5 circuit it is replaced by a very small transformer and full-wave rectifier. This circuit is connected to the ac line at all times, but only draws a few watts.

In bench tests the above SI-5 circuit reached 300 watts ac output easily. Higher power levels were not attempted because our stock of transistors is running low, and because this unit has smaller heat sinks than the SI-4 unit, and these heat sinks get hot rapidly at the 300 watt level. The SI-4 unit which has only 2 transistors instead of 4 could only reach 250 watts ac output. These results demonstrate that the output can be increased indefinitely by paralleling transistors. Eventually, of course, other components would have to be increased in size as the power level is raised. The most expensive component is the output transformer, whose cost varies roughly as the square root of its power rating.

Bench Test Facilities

We have facilities for a variety of bench tests. Prior to this Grant period we tested the efficiency of a Delco alternator in a two-step process. First we measured the drive motor rpm for various alternator output voltages and currents. Then we detached the drive V-belt and measured the motor torque with a weighted-cord arrangement for various motor rpm's and calculated the corresponding mechanical output power of the motor.

For most of our inverter bench tests, we used this same induction motor to drive the alternator which in turn supplied power to the inverter under test. Because induction motors have nearly constant speed, regardless of voltage and load within their allowable operating range, we had to change motor pulleys to vary alternator speed. For the most recent tests we replaced this motor with a compound-wound dc motor and variable-voltage dc supply. The torque and rpm characteristics of such a motor as a function of supply voltage are reasonably similar to the torque and rpm characteristics of a wind rotor as a function of wind speed, so this system was particularly useful in testing the operation of the power level control circuit in the synchronous inverter.

For measuring ac power to the line we have three watthour meters kindly supplied by the Montana Power Company, and for more convenient instantaneous power measurements we purchased an ac wattmeter.

Not quite in the bench test apparatus category is a solidly built test tower for mounting a small windmill in the back of a pickup truck. This was never used, but would be handy in checking rotor characteristics vs. wind speed more quickly than can be done in ordinary field tests.

Bench Tests of Inverters

Certain results of our bench tests of our synchronous inverters, as well as a brief bench test of an induction motor acting as an induction generator, are presented in Appendix B. Results of an early test, when we were using power transistors instead of the power Darlington transistor combinations we presently employ, are shown on page B-1. We had difficulty then with pips appearing on the current waveform for output power above 150 watts for this circuit which only employed two power transistors. This difficulty does not occur when the Darlingtons are used.

The results on page B-1 show that efficiency as high as 68.5% was achieved, which is not too much lower than the maximum theoretical efficiency of 78.5% ($\pi/4$) attainable with this type of circuit. An analysis of the power losses appears on page B-2. It is evident that for operation at lower voltage the heat losses in the alternator rise rapidly with increasing output power. At low output power, the power required by the alternator field reduces system efficiency substantially.

A recent bench test illustrated the effect of this field power requirement quite dramatically. A compound wound dc motor was used to run a Delco alternator connected to the SI-5 inverter. The torque vs. rpm characteristics of this motor as a function of supply voltage are similar to the torque vs. rpm characteristics of a wind rotor as a function of wind speed. As the motor supply voltage was increased, the rpm increased until voltage build-up in the alternator occurred. At this rpm the alternator requires maximum field current of about 2.5 amperes at 14 volts, and the motor supply power had to be increased considerably before the alternator would speed up enough for the inverter to cut in. As the alternator speed increases, the required field current decreases, so at the same dc input setting the rpm increases considerably once this "field power barrier" is broken through. For operation at 22 volts, generator voltage build-up does not occur until a higher wind speed is reached, for which there is enough power available so that the "field power barrier" is much less important. This fact, together with the fact that the alternator is more efficient at 22 volts and the inverter puts out more power for the same number of transistors at this higher voltage, makes it appear that 22-volt operation is more desirable than 14-volt operation, even though somewhat higher wind speed is needed for cut-in.

Bench Test of Induction Generator

Recently, several people have suggested to me the possibility of using induction motors as induction generators in wind systems, and Don Brelsford gave me the manufacturer's information on the Enertech Model 1500 system of this type. Its combined wind rotor and induction generator efficiency of 66.5% at 12 mph looks suspiciously high - perhaps their truck speedometer was off or possibly they were multiplying voltmeter and ammeter readings together rather than measuring power (An induction generator will have current out of phase with voltage, especially at low output, so the power is $VI\cos\theta$, where θ is the phase angle between the voltage and current sine waves.)

At rated 1.5 kilowatt output at 22 mph the combined efficiency of 32.5% is believable.

For a quick check of the induction generator idea, I set up the apparatus shown on page B-3 and obtained the results shown therein. The set-up consisted of a 240-volt ac variac whose rectified output drove a compound-wound dc motor, which in turn drove an ac induction motor by means of a V-belt. The induction motor, acting as an induction generator, was connected to the 120-volt ac line through an ac wattmeter. This motor was rated at 1/6 horsepower, which is equivalent to 125 watts, but was able to deliver 200 watts ac to the line for ten minutes before becoming very hot to touch. At this power level, the dc drive motor consumed 900 volt-amperes ac, and I assumed power factor of 1, or 900 watts ac power in. I made no mechanical power measurements, but estimate that this 900 watts was divided as follows: 300 watts heat loss in dc drive motor, 100 watts heat loss in belt drive, 300 watts heat loss in induction generator, 200 watts ac input into line. If this assumption is correct, this induction generator is 40% efficient under these conditions. The tests confirmed two characteristics that one would expect for induction generators: their speed within proper operating range is nearly constant, varying in this case from 1800 rpm at zero output to 1850 rpm at 200 watts output, and the power factor is bad, with the generator drawing 4.3 amperes (about 500 volt-amperes) at 0 watts output.

To summarize pros and cons of ac induction generators vs. dc generators connected to synchronous inverters, as means for feeding power into the ac line:

1) The induction generator is nearly a fixed-speed device and thus will work efficiently with a fixed-pitch wind rotor only for a wind speed range of a factor of 3 (say 10 to 30 mph), while a dc generator is suitable for variable-speed operation.

2) The dc generator/synchronous inverter system requires for efficient operation a control to match power output to windpower available as wind speed changes, while the induction generator achieves this matching automatically.

3) Certain synchronous inverters (ours and presumably that of Real Gas and Electric, but not the Gemini) put current into the ac line in phase with the voltage as desired by the utilities, while the induction generator has a poor power factor, with current out of phase with voltage by nearly 90° at low output levels. The power factor could be corrected by putting a large capacitor in parallel with the generator, but the capacitor would cost about as much as the generator.

4) A dc generator will cut in automatically at the proper rpm, but an induction generator must have an accurate control device which will cut it in slightly above synchronous speed and cut it out at synchronous speed, to prevent its operating as a motor at lower rpm.

5) Induction motors and automotive generators are both widely available new and used, at low cost, but synchronous inverters must be constructed at non-negligible cost.

6) Comparable efficiencies can be expected for both types of system.

Field Test Site

We obtained permission from the MSU Department of Veterinary Science to use an open plot ¼ mile west of their laboratory as our test site. We purchased fifteen poles of about 25-foot length which the Montana Power Company kindly placed into the ground. Twelve of these are for the ducted rotor tests, one is presently supporting our sailblade rotor, and the other two support the 120-volt ac lines which allow the power generated to be fed into the utility grid. The power line brought from the Veterinary Research facilities runs first to a circuit breaker and then to two watthour meters. The line from one meter runs to the ducted rotor area, while the other line runs to a trailer on loan from the MSU Research Office. A cable of four wires runs from the trailer to the pole supporting the sailblade rotor system. This arrangement allows the synchronous inverter for this system to be sheltered in the trailer. The trailer is also used to store tools and spare parts. An anemometer is mounted on one of the power line support poles, while another anemometer is located in the throat of the ducted rotor wind barrier. All of these facilities are located well away from buildings, trees, or other obstructions which would hinder wind flow. The average wind speed there is 7 mph.

Barrier for Ducted Rotor Tests

Plan and elevation views of this barrier appear on page B-4. The poles were installed in December, 1977. Guy rods for the poles and a criss-crossed framework of 1/4 - inch steel rods for the east and center panels were installed in spring, 1978, and the Hypalon irrigation dam plastic material was attached to the framework that summer. During summer, 1979 these vertical Hypalon barriers were extended 10 feet westward to provide a Venturi which expands from 10 feet wide at the throat to 17 feet wide at both ends. Until then there had been a diffuser section which only expands eastward from 10 to 17 feet, with the three-blade Krueger rotor mounted at the west end of the diffuser. The axial dimensions are: 10 feet for the added west taper section; 5 feet for the constant 10-foot-wide section immediately east of the rotor; and 10 feet for the east taper section. The Hypalon wall is 13 feet high, centered at the rotor height of 15 feet. A simplified framework of two 1/2-inch horizontal steel bars was used between each pair of poles for the added section, as can be seen in Figs. 4 to 6 which are photographs taken before the sheets were put up. The Hypalon is attached to the posts by bolts and nails running through grommets in the Hypalon, and also to two threaded studs welded to each horizontal bar.

Before the barriers were extended, the anemometer in the throat of the duct rarely registered as much as the anemometer in undisturbed air. With the extension, when an east wind is blowing the anemometer in the duct registers about 10% higher wind speed, even though it is blocked somewhat by the 3-blade Krueger rotor (which doesn't turn in east winds). This corresponds to about 33% more available power. The increased power doesn't compensate for the expense of the barrier, but the duct is useful for rotor and inverter testing.

Field Test Results

During tests in spring, 1978 our sailblade rotor with a V-belt driving the alternator started to turn in 7 mph winds, put out 300 watts resistive load, and survived an estimated 40-mph wind while free-wheeling. That summer we replaced the V-belt and pulleys with a toothed belt and toothed pulleys and connected the alternator to the SI-5 inverter. With the toothed belt (timing belt) instead of the V-belt it started in a 4-mph wind, indicating that friction had been reduced by a $(4/7)^2$ factor. The system received a good test from the wind of Nov 4, 1978, which averaged 26 mph during a typical 15-minute period and gusted to perhaps 40 mph. This wind lasted for about 10 hours. With the voltage regulator in series with a Zener diode for 22-volt dc output, the system cut in at about an 18-mph wind, while without the Zener for 13-volt operation only a 9-mph wind was needed for cut-in. At an average 26-mph wind with the controls set for 100 watts ac output (200 watts dc input) the inverter was operating most of the time. This power did not seem to load the rotor excessively. The springs which at that time allowed the blades to feather were in operation much of the time. Perhaps a higher tension in these springs would have allowed higher speed and higher efficiency operation of the rotor. Also, the speed ratio of the alternator relative to the rotor is only 20:1 (60:14 sprocket tooth ratio and 84:18 pulley tooth ratio). A higher ratio would reduce the cut-in wind speed, especially now that friction has been reduced by using the timing belt.

This synchronous inverter, operating at 22 volts DC input, cut in at about 15 mph wind speed. After bypassing the Zener in series with the voltage regulator so the system would cut in at 14 volts, a wind speed of 9 mph was needed for cut-in. On Nov. 19 I found that one of the cables on the sailblade rotor had broken where it ran over its pulley, so I took down the blades for reconstruction without protective springs as described previously.

On Feb. 25, 1979, the sailblade rotor was replaced as modified without the protective springs and pulleys, and on March 4, the system cut in at 14 mph winds. I loosened the cables subsequently to increase the torque (which of course tends to decrease the no-load rpm), and found on April 20 that the system cut in from 1/2 to 2/3 of the time at 18 mph average wind speed, and did not cut in at all when the speed average dropped to 14.5 mph. On April 24 with an east wind averaging 24 mph, the power output averaged 50 watts ac. (The SI-5 then had a Variac in its ac line to allow operation with the transformer which has a turns ratio suited to 22 volt dc input; this Variac cuts efficiency and output power somewhat).

On April 2 the Krueger system was installed in the throat of the duct, facing west so it is responsive only to westerly winds. The SI-5 inverter was transferred to this system on April 28th. It was put under a weatherproof cover and is shown (with cover raised) in Fig. 8. On May 4, a west-southwest wind of 24 mph gave 210 watts average input and 56 watts average output, with a maximum of 80 watts output noted. On May 5, southwest winds of 13 mph did not cause cut-in, but 25 mph was sufficient for cut-in. On May 6, west-northwest winds of 12 mph were not sufficient for cut in, but 17 mph caused the inverter to cut in about half the time. The rotor was not noticeably loaded when cut-in occurred, indicating that a higher speed-up ratio to the alternator might be advantageous. No directly west winds occurred while the system was being observed, except for west winds up to 9 mph which were too slow to cause cut-in.

The rather indefinite results on cut-in wind speed (range from 9 to 18 mph for 14 volt dc operation with the sailblade rotor) may result from an unstable region of operation near cut-in speed caused by large field power requirements at low speed as described in the bench test results section.

Other Work

Daily readings were made of the anemometer on top of the MSU Physics Building and of the anemometers at the test site. Records of these readings and of our other test results are available on request.

Our evaluation of the vortex wind machine concept appears in Appendix C. Our report on a visit to the Oklahoma State University wind project, with its bicycle-wheel-type rotor and variable speed-constant frequency alternator, appears in Appendix D.

Personnel

A number of students and staff worked with me on this project, some for pay and some for research credit. These include graduate student Chris Smith, undergraduates Dan O'Reilly, Dan Rennie, Steve Bredberg, Jim King, Al Timm, and Jim Boschert, physics electronics shop personnel Bob Glade and Harley Herndon, and Prof. Richard Rosa who contributed the ducted rotor and vortex system analyses.

System and Project Costs

Estimated costs for our three systems less synchronous inverters are detailed below. In each case it is assumed that the windmill is mounted on a wooden pole braced by three guy rods. Amounts are for small production quantities with semi-skilled labor at $5 per hour.

Item	8-foot Al Blade	10-foot Sailblade	7-foot Krueger
Hor. & vert. axis bearings	$30	$30	
Tailfin material	40	none	
Rotor material	100	70	
Rotor platform material	10	10	
V-belt and pulley	15	15	
Alternator	30	30	
SUBTOTAL	$225	$155	$185
Sprockets and chain	30	30	none
Idler bearings	15	15	none
TOTAL PARTS	$270	$200	$185 (kit)
Blade labor	40	70	150
Tailfin labor	20	none	10
Alternator drive installation labor	20	20	5
Rotor platform installation labor	30	30	5
TOTAL COST LESS MOUNTING	$380	$320	$355
Pole and bracing	50	50	50
Pole installation	50	50	50
SYSTEM COST	$480	$420	$455

In our Final Report on the Synchronous Inverter Development project, dated February 15, 1978, we estimated production cost of a 600 watt ac output synchronous inverter with power level control but without transient protection at $200. A more practical option might be to do without the power level control but keep the transient protection used in our present units, in which case $200 still seems a reasonable estimate.

The Venturi-shaped barrier for the ducted rotor system required 75 square yards of Hypalon irrigation dam plastic, which cost $187.50. The eight poles on which it was mounted cost about $200. The steel framework and mounting hardware cost about $100, for a total materials cost near $500 for this duct which will accommodate a rotor up to 10 feet in diameter.

As of June 30, 1979, the following amounts have been spent by Montana State University on this project:

Category	Amount spent	Budget
Salary and wages	$14,495.60	$10,506
Benefits	1,186.03	1,148
Travel	303.73	300
Communications	37.99	100
Supplies	3,529.44	2,100
Other services	- - - -	400
Subcontract	52.02	- - -
Rent (scaffolding)	547.60	- - -
Equipment	823.50	1,590
Awards	7.34	- - -
Indirect Charges	4,704.52	3,496
TOTAL	$25,687.77	$19,640

In addition, since September of 1978 I have spent $540 of my personal funds on supplies for this project, so the project support sources are: DNRC - $19,640, MSU - $6,047.77, VHS- $540, for a total of $26,227.77.

Economic Evaluation

The projected small-scale production costs of our three wind systems, each with a 600 watt synchronous inverter operating at fixed power level, were comparable. The Krueger 7-foot wood rotor system with expected cost of $655 will be used in this calculation because it has the best-defined cost. For 20-year life, 10% interest on a 20-year loan of $655 taken out to buy the system, and with maintenance costs compensated by 10% salvage value, the annual cost of the system is $76. If this system has the duty factor of 30% typical of wind systems, its average output will be 180 watts, or 1,578 kw-hr per year. If this power replaced utility power at 4.8¢/kw-hr, the owner would just break even. For another comparison, if retail power presently costs 2¢/kw-hr and increases 10%/yr in cost, then in 20 years the wind system owner would pay $1,520 for the system but would save $1,808 on utility bills.

If the generator and inverter together have 40% efficiency and the wind rotor has 60% efficiency relative to the theoretically possible 16/27 kinetic energy extraction, a steady 180 watt ac output would require a steady 18 mph wind for this 7-foot rotor. Because any location has a distribution of wind speeds, this required effective 18-mph wind speed corresponds to a lower average wind speed. A convenient distribution function which fits fairly well the measured wind speed distributions as graphed by John Obermeier in his M.S. Thesis (MSU Mech. Eng. Dept., 1976) is Kue^{-u^2/u_o^2}, where $u_o = 1.1284u_a$, u_a is average wind speed, u is actual wind speed, and $K=2/u_o^2$. For this distribution, the effective wind speed is $1.24u_a$ for an ideal rotor running at optimum speed which is linearly related to wind speed, and $1.20u_a$ for an ideal rotor running at a constant rpm which is optimally chosen for the wind distribution. Accordingly, for our 7-foot rotor system example, a location with average wind speed of 15 mph is required, which is available only in the windiest Montana locations. Details of these calculations are available upon request.

An interesting and perhaps important result of this calculation is that for ideal rotors and this wind speed distribution, the average power attainable if rotor speed is varied so as to optimize power output as wind speed changes, is only 10% greater than the average power attainable if rotor speed is held fixed. This surprisingly small difference occurs because the power distribution curve is a rather sharply peaked function of wind speed u proportional to ($u^4 e^{-u^2/u_o^2}$ for our chosen wind speed distribution; actual power distribution curves for Montana locations appear in Obermeier's thesis). This implies that a power level control to allow optimum rotor speed for all wind speeds should not add more than 10% to the wind system cost, or $65 additional for our example system. A control system would have to be quite simple at that price.

We have already pointed out that an induction generator runs at nearly constant speed over its proper operating range. What is perhaps not so obvious is that a generator/inverter system which has a constant operating power level is also essentially a constant speed system. The generator cuts in at a certain rpm, but if the rotor cannot supply the power required by the inverter, the rotor will slow up somewhat and the generator will cut out. This cycle will repeat, and the average power output will be the power available at that rpm. Only for wind speeds high enough so that the available power is greater than the required power, will the rotor speed increase above cut-in speed.

III. CONCLUSIONS AND RECOMMENDATIONS

Wind Rotors

We have built and tested three rotors of entirely different types:

1. Eight-foot diameter with four constant thickness aluminum blade.

Mechanically this is by far the sturdiest of the three, showing no deterioration after five years of use in a location with 4 mph average wind but occasional strong winds. The material is rather expensive and the construction time is moderate. Its efficiency is only fair, because of its constant-thickness section and large blade area. Tests of this rotor with two blades showed extreme vibration of the mounting post when wind changed direction, confirming Jacob's assertion that three or more blades are desirable if undamped vertical axis reorientation is allowed.

2. Ten-foot diameter with five spars and attached Neoprene sailblades.

Has been tested in 7 mph average winds for one year. Automatic feathering device did not hold up well but probably could be made reliable. Overspeed without such protection did not prove to be a problem in this location. Material is not expensive and perhaps cost could be further reduced by using wooden instead of aluminum spars. Construction time is moderate. Efficiency is rather low because spar drag is high and blades have constant thickness and pitch. Spar drag could be reduced by bringing Neoprene around both sides of the spar in a teardrop shape. Pitch varying with radial position could be provided by using a trapezoidal-shaped blade with two cables of differing tension attaching it to the neighboring spar. Both this and the aluminum-blade rotor are low-speed rotors for which balancing does not seem to be critical but a two-stage speed increase is required to drive high-speed generators.

3. Seven-foot diameter Krueger rotor with three wooden airfoil-shaped blades.

Has been tested for five months in seven mph average winds. Material is inexpensive but long assembly time is required. Operates at high speed so only one stage of speed increase to generator is required, but must be balanced carefully. We had no experience with possible balance problems caused by icing. As with the other two rotors, running without load did not cause overspeed-related damage. Some shrinkage of wood caused cracking of the fiberglas outer layer at the hub. The mounting setscrews work loose and the support bearing developed play, so these provisions should be redesigned. It is easily the most efficient rotor of the three.

Generator Drive Trains

Generator drive by V-belt is the least expensive, but particularly at lower wind speeds their friction reduces efficiency, and they need occasional tightening and replacement. Use of a toothed belt and pulleys reduces friction considerably, and in ten months of testing with the sailblade rotor the belt has held up well. The increased system cost is about 10%, but the resulting power output increase is probably greater. Bicycle chain in the generator drive stage proved noisy and unreliable.

Trail bike chain and sprockets were used in the rotor-to-idler stage for the two low-speed rotors, and proved quiet and reliable. The small sprocket in the aluminum-blade rotor system had to be replaced after five years. Friction bearings used for the idler shaft showed considerable wear after that time, so more expensive ball bearings are probably preferable.

The added expense and assembly time for a two-stage speed increase is an important reason for considering use of a high-speed wind rotor which only requires one stage of speed increase to the generator.

Generators

The Delco automotive alternators with built-in diodes giving dc output which we have used with all three systems have proved reliable even under exposure to weather extremes, and are quite inexpensive. They are inefficient in low winds because the field then requires a large fraction of the output power, and are also inefficient for high output currents because of internal heating losses. Efficiency can be increased from 45% to 65% by increasing operating voltage from 14 to 28 volts, but then the cut-in speed becomes higher. For large-scale production a more efficient and lower-speed generator might prove economically advantageous.

The commonly available, inexpensive and reliable single-phase ac induction motor can be used as an induction generator to feed power into the line. Its efficiency is comparable to that of the combined efficiency of our generator-inverter systems. Utilities would probably require parallel capacitors, of cost comparable to induction motor cost, to bring the generated current into phase with the line voltage. Induction generators are probably an economically viable alternative to our alternator-synchronous inverter system for supplementing utility power. However, for independent operation the control circuitry required to maintain constant frequency and voltage with changing load probably would be too expensive for small systems.

Provisions for Aligning Rotors with Wind

One can either align the wind with the rotor, or the rotor with the wind:

1. Ducted Rotor. With this approach the rotor orientation is fixed, and a fixed duct is provided to direct the wind along the rotor axis. Our experience with our Venturi-shaped vertical-wall duct has been that the time and material expense in constructing the barrier is not warranted by the small increase in average wind velocity obtained.

Agricultural benefits of such barriers seem too small to tip the economic balance in their favor. However, if a duct is already available in the form of a gap between two cylindrical grain storage bins or even at the corner of a large building, it might pay to locate a fixed-orientation rotor in such a duct. The expense of providing vertical-axis reorientation capability would thus be avoided. A sailblade rotor has the advantage in this application that it will operate equally well with wind in either direction along its axis.

2. Rotor which can reorient to align with wind. Our aluminum-blade rotor system has a split tailfin which points the rotor into the wind except for high wind speeds, at which it folds together and turns the rotor sideways to the wind. Such protection may not be necessary; our downwind sailblade rotor system without a tailfin has not suffered from overspeed. The Krueger system has a fixed tailfin which we did not use because we mounted this rotor in our duct. Downwind rotors seem preferable from the standpoints of cost and simplicity.

Inexpensive and strong bearings for both vertical and horizontal axis rotation can be provided by used automotive front hubs. Brushes must be provided for electrical contact unless vertical rotation of the platform is limited. A fixed rotation stop has certain problems which we have attempted to avoid by constructing a variable-torque stop. This stop has not yet been tested.

Synchronous Inverters

Our synchronous inverter design, based on transistors in a push-pull configuration driving an output transformer, has proven reliable and reasonably efficient. It provides a sinusoidal current waveform in phase with the line voltage. Our power level control, which serves to match power output to power available at different wind speeds, works well. We have shown that output power can be increased by paralleling transistors. We have also shown that our circuit with modifications can act as an independent inverter. We have considered circuit modifications which we believe will increase its efficiency.

The Gemini synchronous inverter, based on silicon-controlled rectifiers (SCR's), has high inverter efficiency and moderate cost, but its current waveform is intermittent. This leads to lower generator efficiency, and may also lead to opposition from utilities.

The Real Gas and Electric Co. synchronous/independent inverter has high cost, but is said to have high efficiency and good current waveform. This unit will be field tested by DNRC during the next year, and bench tested by us in autumn of 1980.

Overall Systems

1. Vortex system. Our analysis shows that the performance of this as-yet-untried system is difficult to predict. It would seem to require a large amount of material in its construction for a given effective area.

2. Chalk Rotor and Variable-Speed, Fixed-Frequency Generator.

This rotor, which resembles a large bicycle wheel with airfoil-shaped sheet aluminum blades supported by the spokes, seemed rather flimsy to me but is in production driving variable-frequency generators which in turn power pump motors. Oklahoma State University researcher, Dr. Ramakumar, claims that his variable-speed, fixed-frequency generator and associated control circuitry is economically competitive in the intermediate-power range.

3. Small Systems with Synchronous and/or Independent Capability.

Analysis indicates that a system such as Krueger's with a synchronous inverter scaled up from our design would be close to being economically attractive. Combined synchronous/independent inverters would be attractive to the large number of people who for various reasons want the option of independent power generation and it would seem that such inverters could be produced at an attractive price. Single-phase or three-phase induction generators also seem to be a practical option in the low to medium power range for shared-grid, but not for independent, operation.

IV. MONITORING

During my sabbatical leave the three wind generation systems will not be operational. The aluminum-blade rotor system was taken down this month and is being stored in the basement of the Physics Building at MSU. The Krueger rotor was dismounted and is being stored in the control trailer at the field test site. The sailblade system is still in place at this test site ¼ mile west of the MSU Veterinary Research Laboratory, but the sails have been wrapped around the spars. The main power switch at the site has been turned off.

Arrangements have been made to loan out the four anemometers to study wind speeds at various Montana sites during my year's absence. Two of these were bought with Grant funds and are property of DNRC; the other two belong to the MSU Earth Sciences Department. Permission for these loans was obtained from both agencies. These are totalizing anemometers and do not provide an indication of instantaneous wind speed. One anemometer has been loaned to William Nell (Phone 222-6440)for mounting at his place in the northeast corner of Paradise Valley south of Livingston. Another has been requested by Charles Jackson (Phone 333-4309) who lives near Emigrant farther south in that valley. Kye Cochran of AERO (Phone 259-1958) is undertaking to place the other two. I have recommended that these anemometers be mounted at 15 feet height in an unobstructed location and that they be read daily. Upon my return in August, 1980 I will use the anemometer results to help decide on good windy locations to put up two or three of our wind generation systems for further field tests. I will periodically monitor performance of these systems, which I will locate where someone can make daily wind and power output readings. These systems will be accessible to the public as provided by DNRC rules.

V. PUBLIC AVAILABILITY

Postponement of the period of public availability is requested until my return, after which time I will be happy to show and demonstrate the inverters or systems if prior notice is given, especially for off-campus sites. In the past, I have demonstrated the system to one or two persons or groups a month, including large groups such as attend summer institutes on energy at MSU.

VI. PROGRAM EVALUATION

In general, I believe that the program has been well run, but I was inconvenienced considerably by the delay on decisions on the August, 1978 grant applications, and would recommend that proposal evaluation schedules once announced not be delayed for political considerations.

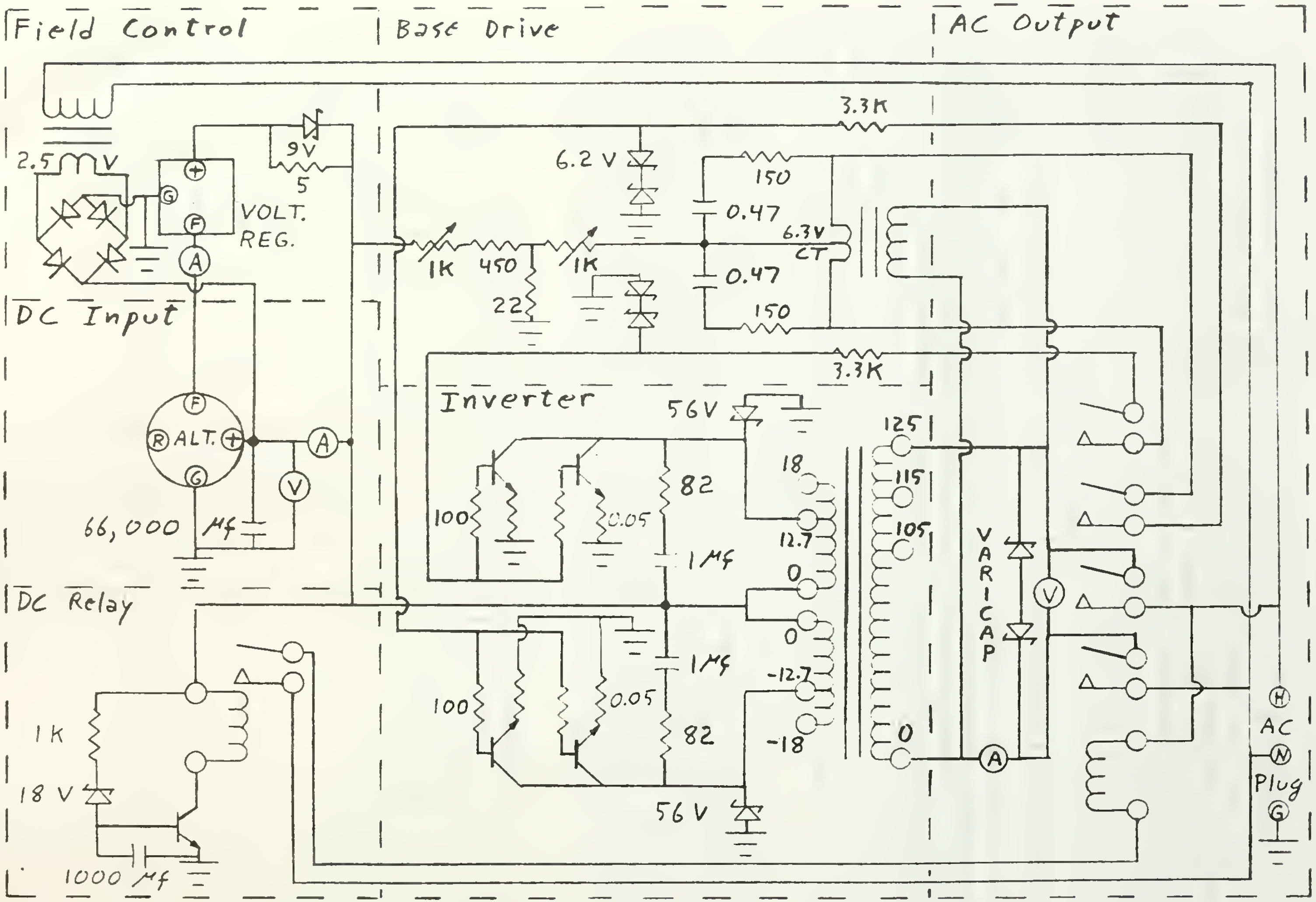


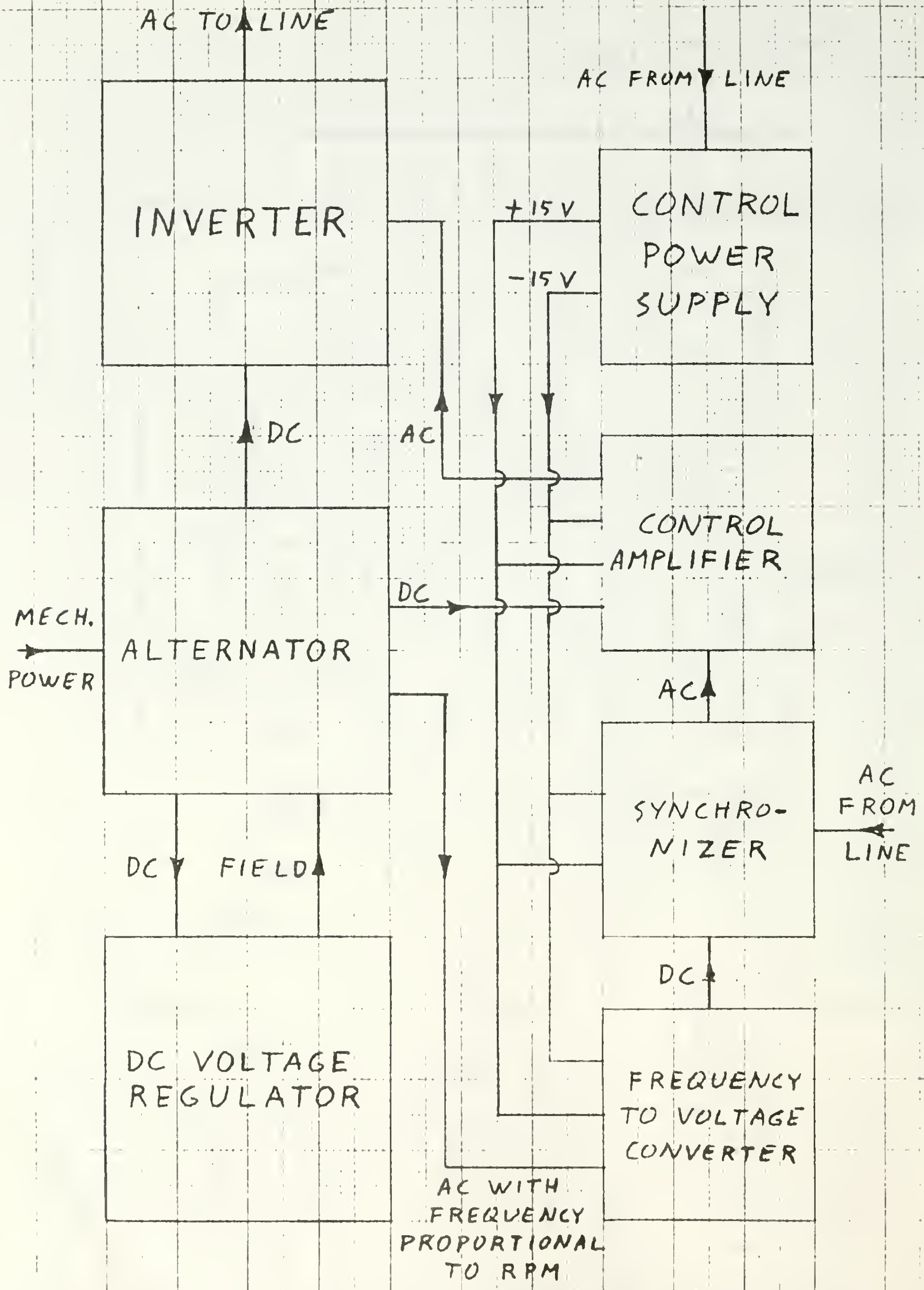
Fig. 9. Synchronous Inverter SI-5 with transient protection.

APPENDIX A

Explanation of Synchronous Inverter Circuit

Each circuit diagram is followed by a page explaining the diagram.

6-21-78



SYNCHRONOUS INVERTER BLOCK DIAGRAM

Synchronous Inverter Block Diagram

Explanation

The 3 larger blocks at left represent all that is required for a fixed-power-output synchronous inverter, consisting of:

Alternator - Converts mechanical power to 3-phase AC with frequency proportional to rpm, and contains diodes which convert this AC to DC.

DC Voltage Regulator - Regulates the alternator field current so as to keep DC output voltage constant as rpm and load change.

Inverter - With aid of control signal synchronized to AC line, converts DC to AC (line frequency) and feeds this AC power into the already-energized AC line.

The 4 smaller blocks at right are needed to match the power required by the inverter to the mechanical power available to drive the alternator.

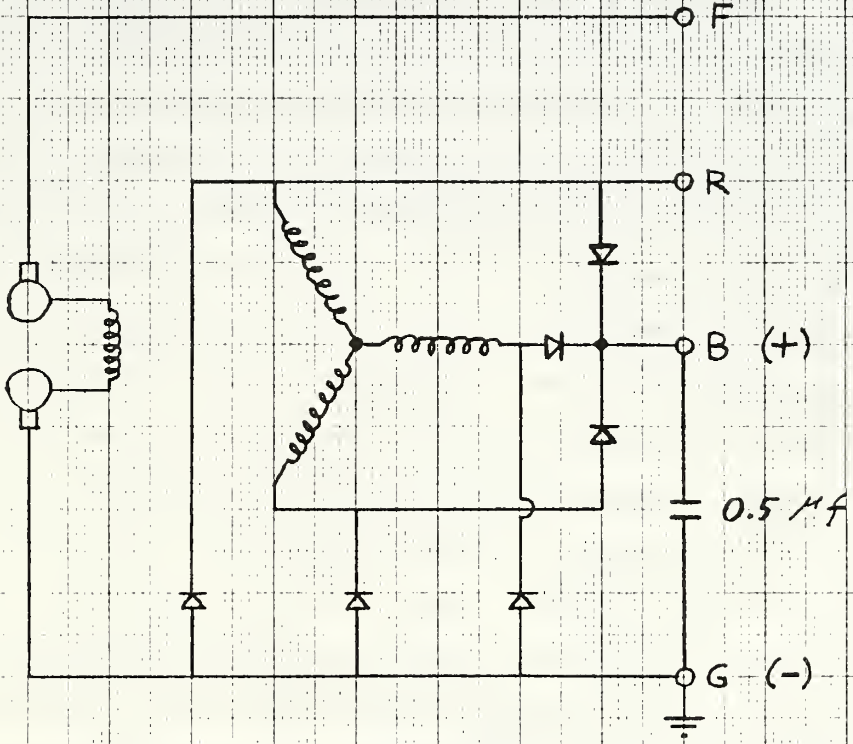
Control Power Supply - Supplies the DC voltages needed to operate the chips in the power level control units.

Frequency to Voltage Converter - Converts a square wave AC signal from the Delco alternator, having frequency proportional to rpm, to a DC signal with voltage frequency, and further processes this signal.

Synchronizer - Clips an AC signal derived from the line at a level proportional to the above DC signal, and then filters the resulting square wave bACk to sinusoidal form.

Control Amplifier - Amplifies above AC signal so it can drive the power transistors in the inverter at the appropriate current level. DC input is needed for proper biasing.

6-22-78
ZHS

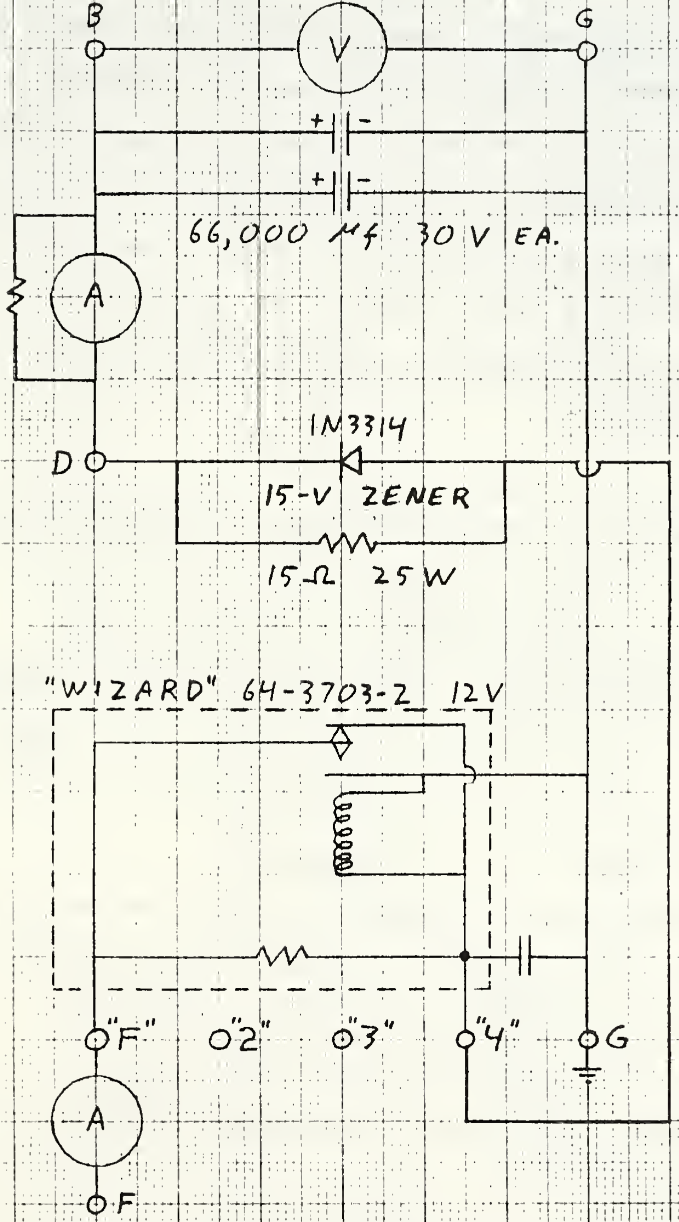


DELCO ALTERNATOR

Alternator

A 12-volt, 55-ampere Delco automotive alternator is used, because of low cost of automotive alternators. The Delco unit has the "R" terminal which provides a square wave AC signal with DC bias, of frequency proportional to alternator rpm. (The rotor has 7 field pole pairs, so rpm = frequency/7.) The "R" signal is used in the power level control. The "F" terminal connects to the field coil thru slip rings. The field coil has approximately 6 ohms resistance, and the field magnets start saturating at about 1.5 amperes field current. The stator contains 3 coils which produce 3-phase AC, whch is full-wave rectified by 6 diodes in the alternator case. The center point of the Y-connected coils is floating. The DC output is taken from the B and G terminals, designated by "BAT" and "GRD" on the alternator. A radio interference suppression capACitor is connected between these terminals inside the case. The case constitutes the "GRD" terminal; it would be difficult to isolate this negative terminal from the case. The source resistance of the alternator is roughly 1 ohm. Its maximum efficiency is about 65% at 30 volts, 30 amperes DC output. The field magnetization responses is too slow to allow field modulation at 60 or 120 Hz.

6-22-78
VHS



VOLTAGE REGULATOR

Voltage Regulator

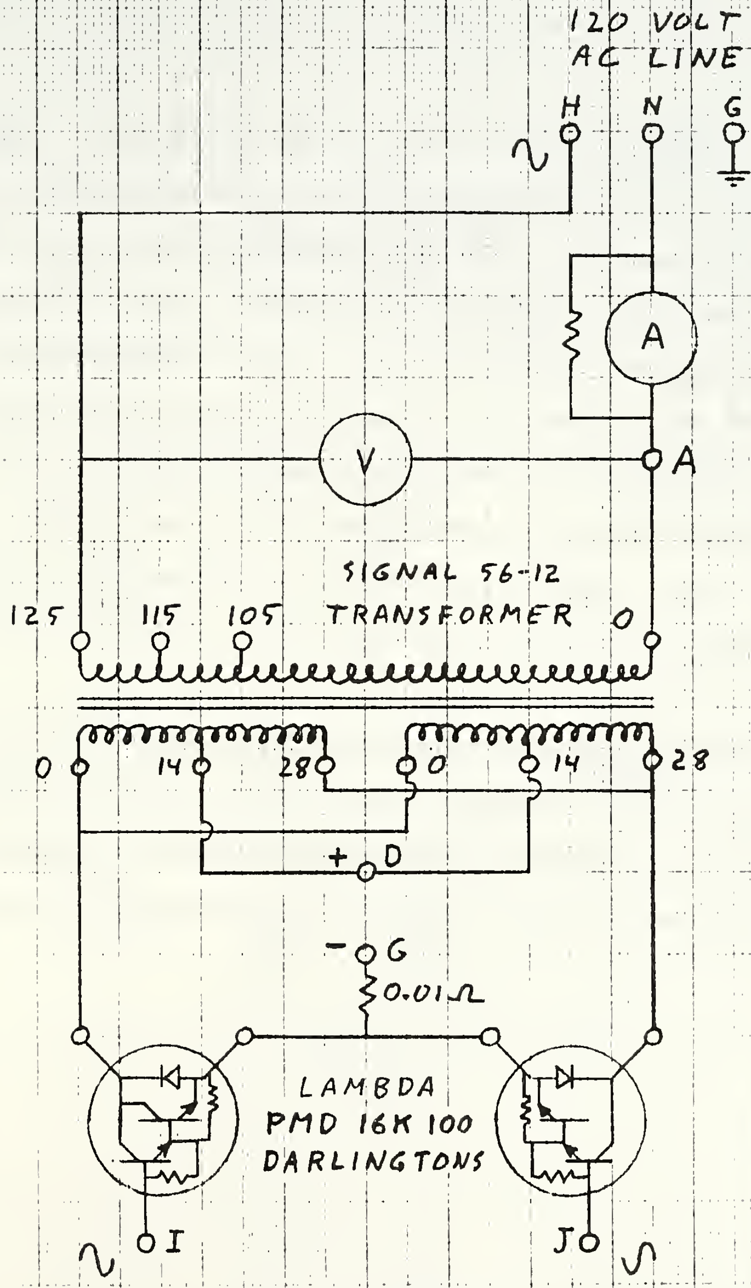
The DC alternator voltage from B is smoothed by capacitors. The DC current passes thru a shunted ammeter to the DC supply terminal D. To use the standard 12-v western Auto stores regulator and yet obtain a higher DC voltage, a 15-v zener is placed in series with the regulator, so that the DC voltage at D is the regulator voltage + 15 volts. A parallel resistor across the Zener is required to allow voltage build-up. Parts of the "wizard" regulator not used in this circuit operation are not shown. The "wizard" "F" terminals connected thru an ammeter to the alternator field terminal F.

An improved regulator circuit would be desirable, as this circuit has 3 drawbACks:

1) With the large capacitors, the voltage level "hunts" with approximately 1 second period and approximately 2 v amplitude; cause is probably in the relay;
2) The circuit requires more power than necessary;
3) For most efficient inverter operation, the DC voltage should vary in proportion to any rms line voltage variations; this regulator is not influenced by AC line voltage.

Despite these drawbacks, the overall circuit functions reasonably well with this regulator.

6-23-78
2HS



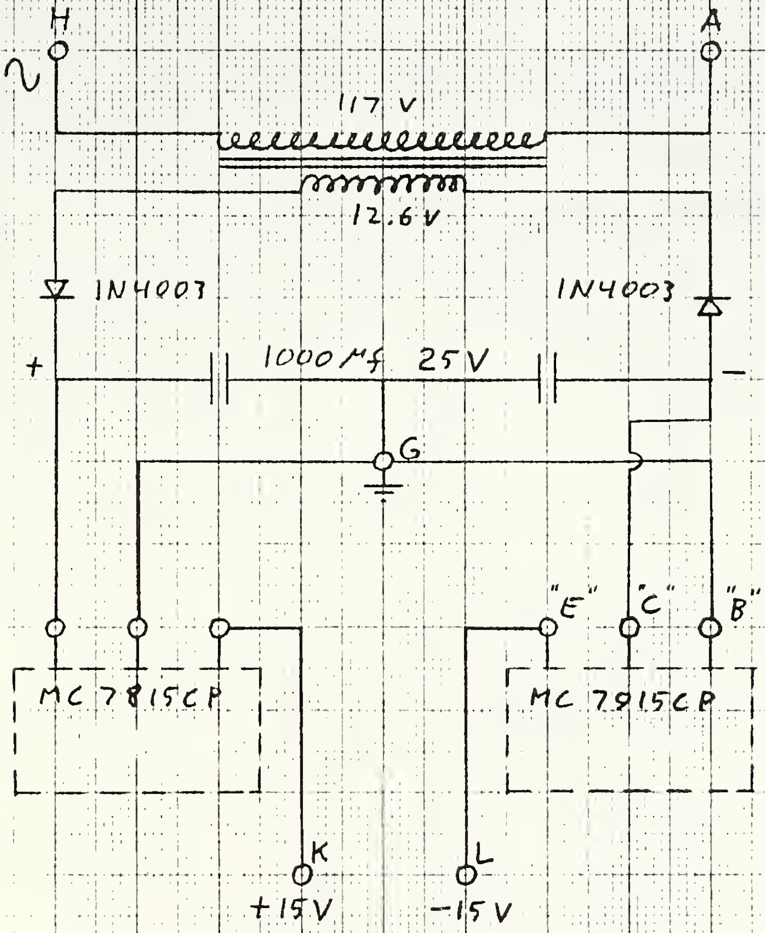
INVERTER

Inverter

60 Hz AC signals of opposite phase are fed into the Darlingtons at I and J. These are synchronized to the line and have the amplitude required to drive the inverter at the desired power level. The bias is adjusted so that each Darlington conducts for half of the cycle, giving half-wave-rectified current waveforms at eACh collector. The effective current into the primary is thus nearly sinusoidal, so the secondary current fed into the line is also sinusoidal. The primary current waveform can be monitored by an oscilloscope probe attached across the 0.01 resistor. An 2c voltmeter and shunted ammeter indicate the line voltage and the current fed into the line. Power fed into the line is monitored by plugging the line cord into a socket connected to both a wattmeter and a watt-hour-meter.

The DC input voltage at D should be just large enough so that the transistors don't cut off when the collector voltage is minimum and the collector current should be maximum. Waveforms and mathematical analysis appear elsewhere. Basically, the circuit is a DC-fed AC current generator which feed AC current into the line.

6-25-78

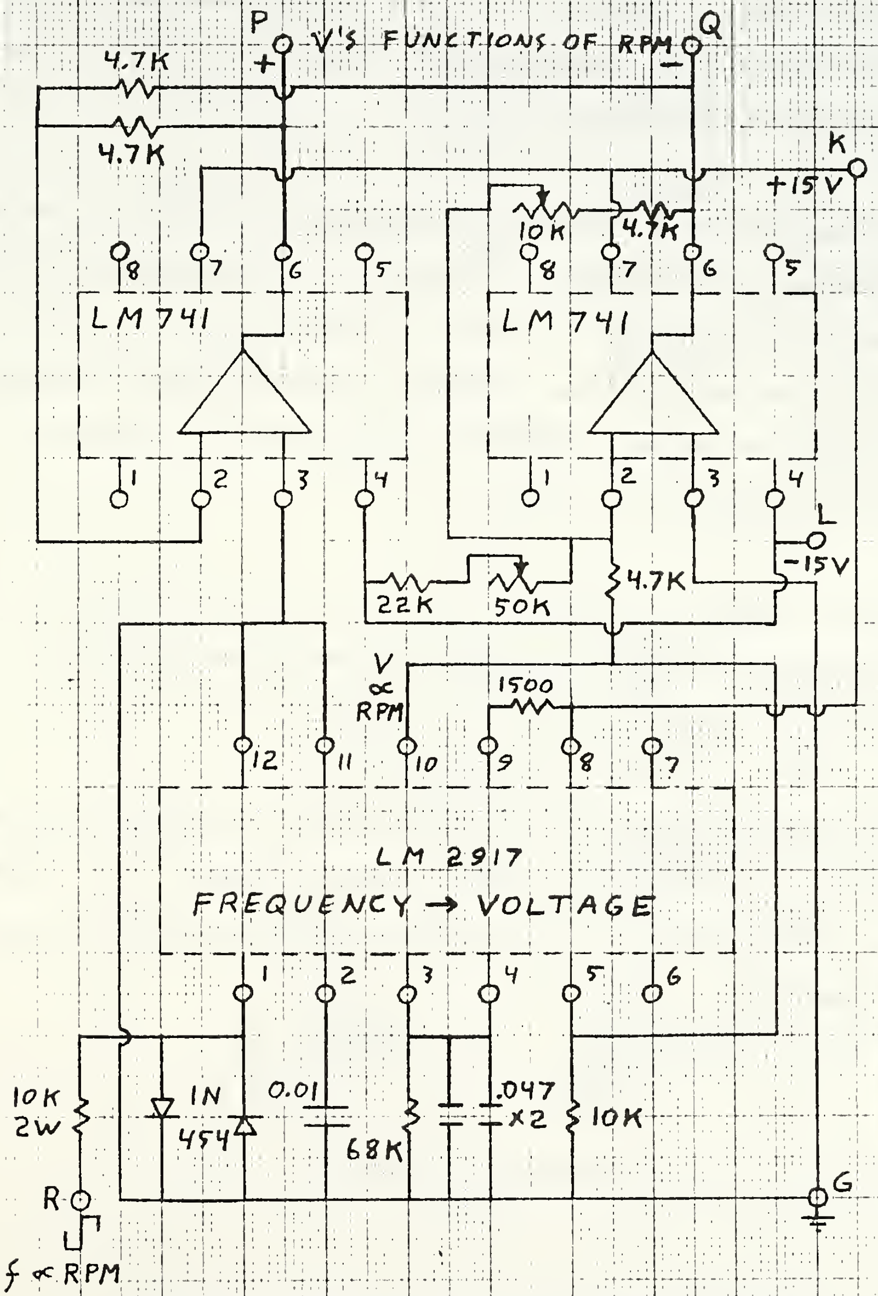


CONTROL POWER SUPPLY

Control Power Supply

This supply takes AC line power, transforms it to lower voltage, rectifies and filters, and then series-regulates it to the +15v and -15v values required by IC's in the frequency to voltage converter and the Control Amplifier.

6-28-78
WHS



FREQUENCY TO VOLTAGE CONVERTER

Frequency to Voltage Converter

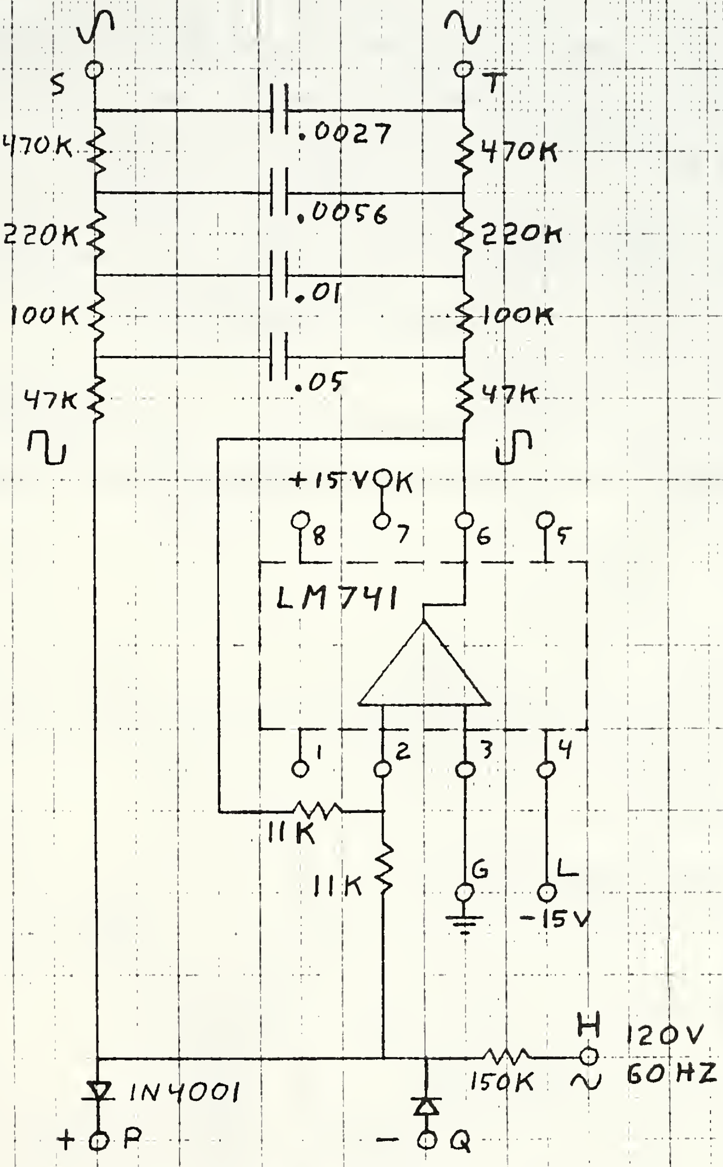
This circuit converts a frequency proportional to alternator rpm to equal and opposite DC voltages which are functions of this frequency. These DC voltages will be used to control the inverter power level.

The AC voltage from the R terminal on the alternator is clipped and fed into the frequency-to-voltage converter chip. The output and a negative signal are fed to the right-hand 741 op amp, which then supplies a negative voltage at Q if the positive current from the LM 2917 is larger than the negative current form the -15v supply, both being fed into pin 2. The left-hand 741 serves to provide at P a voltage equal and opposite to the voltage at Q.

Only if P is positive and Q is negative will the rpm control the power level. For lower rpm giving the opposite polarities, the inverter output will be essentially zero.

The 50k pot determined the rpm at which the inverter will begin to put out power. The 10k pot determines the "slope"; that is, the rate of power increase with rpm increase. Additional op amps could be used to obtain more complete power functions of rpm.

6-29-78
ZHS



SYNCHRONIZER

Synchronizer

The AC line voltage at H is clipped to a square wave by the diodes, with the clipping level determined by the DC voltages at P and Q. These DC voltages are functions of the alternator rpm.

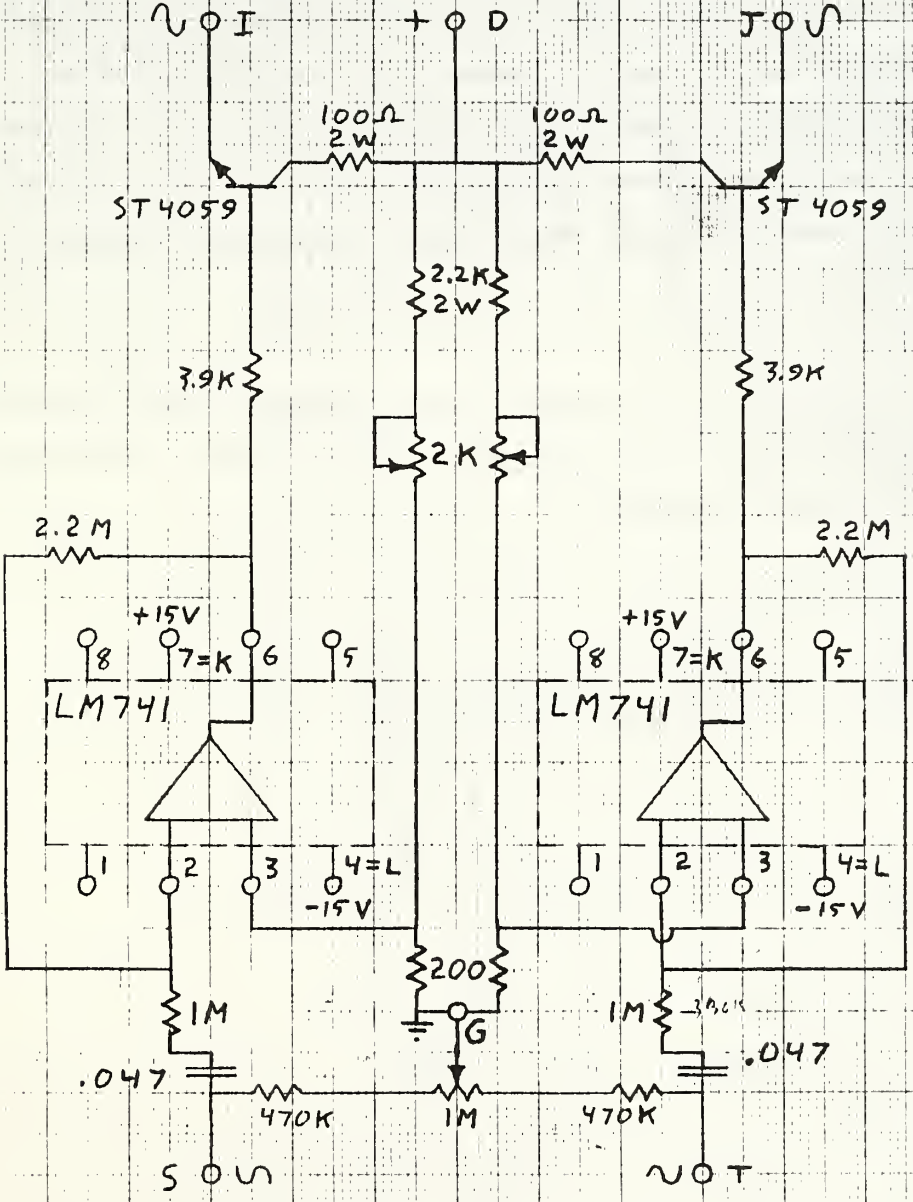
The LM741 op amp inverts the clipped signal. A 4-stage RC low-pass filter restores the signal to sinusoidal form and incidentially shifts the phase by 180°.

The outputs S and T are sinusoidal voltages of equal amplitude and opposite phase, with amplitude a function of alternator rpm, and 60 Hz frequency derived from the line.

Changes made:

1) 500 balance pots installed
   in Darlington base drives
2) 147k AC ref. resistor to look
3) Filter ladder changed.

6-29-78



CONTROL AMPLIFIER

Control Amplifier

The 60 Hz power level control signal from S and T are balance with the 1M pot. They are DC-isolated from the rest of the control amplifier with the 0.047 Mf capACitors. The AC signals are amplified by the op amps, which together with the 3.9k resistors constitute AC current sources for the bases of the ST 4059 emitter followers. These transistors supply the base drive for the power Darlington at I and J.

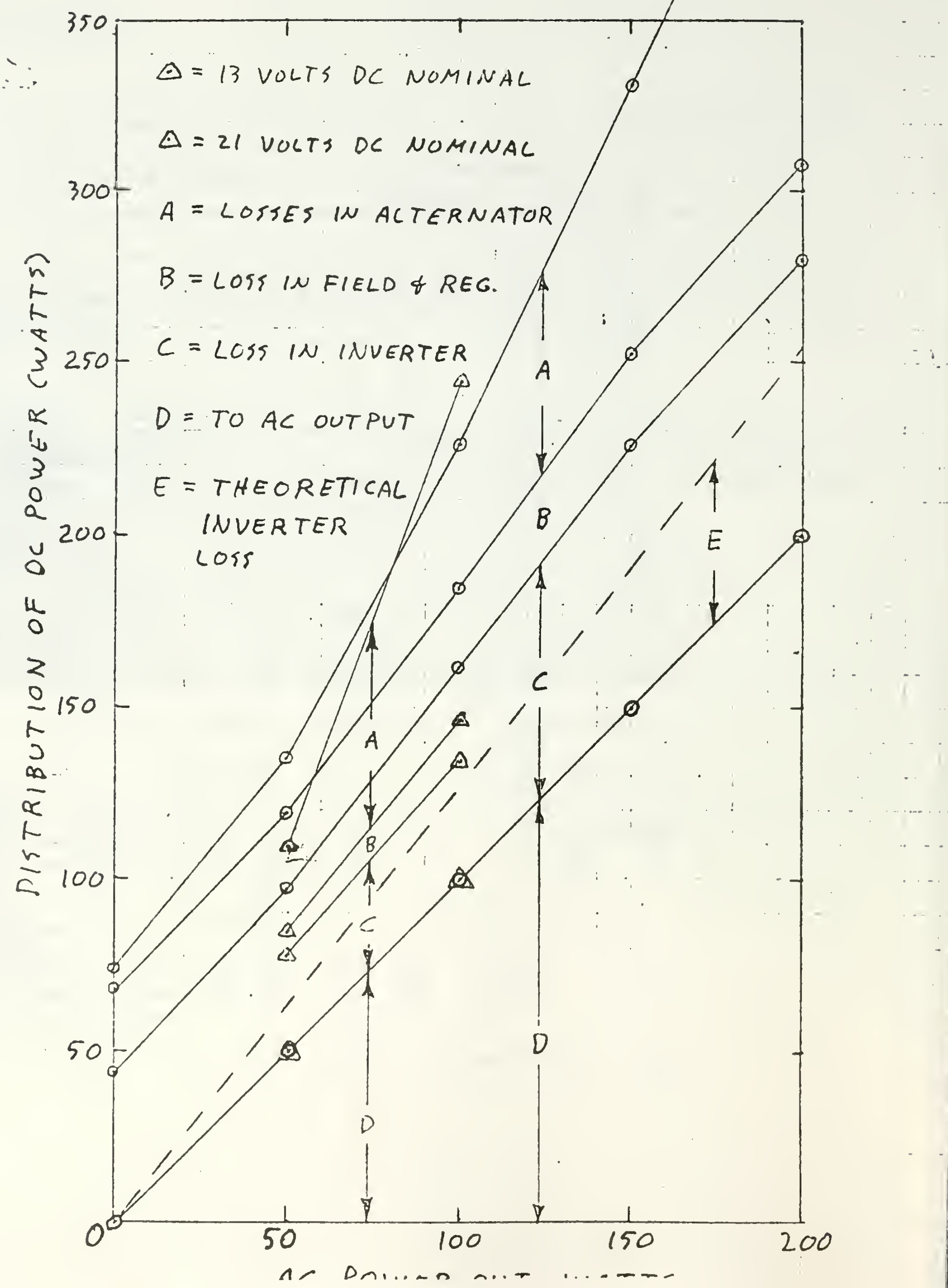
The 2k pots are components of separate adjustable voltage dividers which set the bias levels for the op amps, which in turn control the ST 4059 bias levels, which finally control the Darlington biases.

APPENDIX B

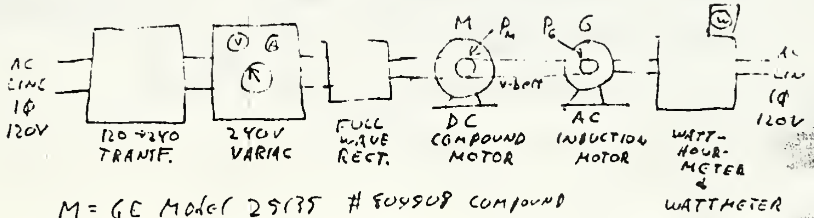
~5100 rpm	alternator				10 V zener			no zener		15 V zener				
DC volts in	20.5				20.0	22.5	20	10.5	13	28 27	28 28	28 28	[illegible] 28	[illegible]
DC Amps in	9.2	9.0	9.2	5.8	12.6	3.0	15.4	13.9	7.0	4.1 1.5	2.1 6.4	15.5 15.5	[illegible] 9.8	13.1 13.
loss @ 0.5 Ω	42	40	42	17	79	4	119	97	24	1	20	120	48	9
DC watts in	189	184	189	119	252	68	308	146	91	40 osc.	179	474	274	37
Field Amps										~.5	.85	1.15	.95	1.[illegible]
Reg. Amps	.70	.68	.70	.60	.80	.55	.90	.60	.47	1.5~1.5	1.5 1.5	1.6 1.62	1.57 .57	1.[illegible]
Field watts										14	24	32	27	3[illegible]
Reg. watts	14	14	14	12	16	12	18	6	6	40 (line)	42	45	44	4
AC volts out	117		115	116	115	137	103	59	75	116 123	117 123	[illegible] 123	[illegible] 123	[illegible] 12
AC Amps out	.90	.86	.90	.40	1.30	.55	1.74	1.51	.45	.37~.3	.95 .52	1.81 .74	[illegible] .91	[illegible]
AC VA out	105	101	104	46	150	75	179	89	34	37	64	214	112	1[illegible]
AC watts out	100+	37	102	50	150	0	200	100	50	0-15	50 50	200 200	[illegible] 100	[illegible]
Meter sec/rev	56			120	39	[illegible]	29							
DC watts out														
Base Variac set.	32			16.2	52.5	7	65	62	47.4	4.5	11.5 3	55.5 62	22 32	[illegible]
out. Variac set.	102		100	101	100	121	98	47	64	[illegible] line	line	110 line	[illegible] line	[illegible]
DC volts max	40					45	39	21	25		25	25	25	27
min	[illegible]		1.5			0	1.5	1.5	1.5		4.5	4.5	4.5	[illegible]
DC Amps max₁	18				30	2	~50	~37	10		12	[illegible] 28	20	3[illegible]
max₂	13				23	1	~38	~28	6.5		8	34 17	14	2[illegible]
min	-2				-3	-2	+20 -10	-3	-2.5		-2	-2	-2	[illegible]
msec min	.2	.8	.2		.1	2	.1	.2	.2		0 1.6	0 .6	0 1.0	[illegible]
max spike	-6		0		-1	0	-4	+3 -1	-1		—	0+7	—	—
Remarks	Fast osc ~5 Hz Vin ±3%			2 Hz osc of Vin ±10%	~10 Hz osc. resistors hot		I(t)	Zener not used	New Aikenwood / Ormsaly & Stalley wattme used, also new wattmete					
Eff. w/o reg.	60.6	60.6	61.8	51.6	66.4	—	71.4	74.1	[illegible]	[illegible]				

SI-4 Power Curves 5-20-78

from data on p. 140



Induction Generator Tests 7-14-79



M = GE Model 25135 # 504908 compound wound motor, $\frac{1}{2}$ HP, 1725 rpm, 220V, 2.25A rated (old)

G = GE Model 5KH 48A 312 resisting split phase induction motor, centrifugal cutout for starting, $\frac{1}{6}$ HP 110 V, 4.0 A, 1 phase 1725 rpm (old model)

Results with P_M = 8" D, P_G = 2" D:

VA in	V	A	W out	Eff.
	110	6.3	0	0%
1080	135	8.0	30	2.8%

?

wrong pulley ratio

7-15-79

P_M = 2.5" D, P_G = 2" D

rpm		V	A	W	Eff.
1800	388.5	185	2.1	0	0
1825 ~~1900~~	580	200	2.9	100	17.3%
	817	215	3.8	190	
	1035	230	4.5	250	24%
DC motor cool	1176	240	4.9	250	
1850 ~~1950~~	900	225	4.0	200	22.2%
		225	3.7	180	
		225	3.8	180	

RPM meas. w. GE Strobotac MSU # 22124

AC Gen somewhat warm,

Start 11:48

11:53 quite warm (Gen)

11:57 Gen. hot, motor cool

31 sec = 175 w

26 sec = 215 w

1770 rpm, draws 4.3 A

Gen. running as motor w/o belt, 39 sec/$\frac{\text{WHMR}}{\text{rev}}$ = 140 watt

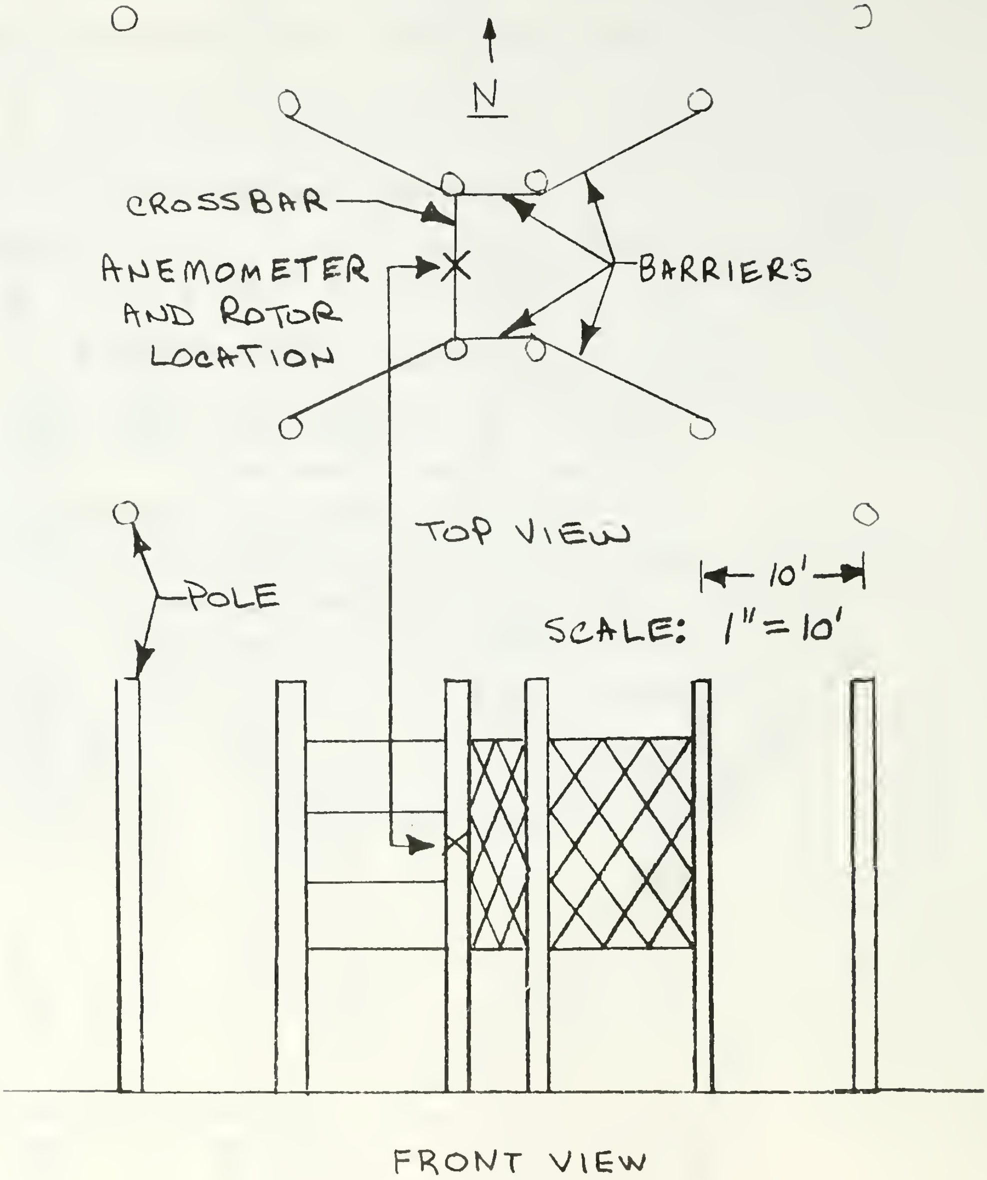
rpm = ~~1850~~ 1750 " with belt, dc motor at 0 V, $\boxed{4.3A}$ 26 " = 215 "

At end of test, motor warm, gen. hot

60W AC into line = 5 A 0 W AC = 4.7A

Guess: 900 w "DC" in ⇒ 300 w heat each in motor & gen.,

[illegible] off.



Barrier configuration at ducted rotor test site.

In our proposal we promised to analyze the suitability of the vortex type wind turbine for small size applications. My co-investigator, Dick Rosa of the MSU Mechanical Engineering Department, has looked into this question and reports as follows:

"One proposed way of augmenting the output of a wind turbine is the vortex or 'tornado' concept illustrated in Fig. 9. The wind turbine, with its axis vertical, is mounted near the base of a tower. The wind, blowing through vanes, which make up the walls of the tower, sets up a vortex within the tower. The low pressure or partial vacuum within the central core of the vortex draws air up through the wind turbine.

nd, solar, and fossil-fuel energy can all be used in
tornado wind energy system. The open vanes
t the incoming wind into forming and maintain-
a vortex or "confined tornado" within the tower.
tornado's force draws air up into the tower and
uses the propeller to spin. The propeller in turn
a generator to produce electricity. Solar col-
an absorb solar radiation to provide addi-
nergy via heat convection to the vortex;
power-plant coolant-water effluent at a
perature of 100°F can be used to heat the sur-
beneath the tower and to provide an upward air
to strengthen and maintain the vortex.

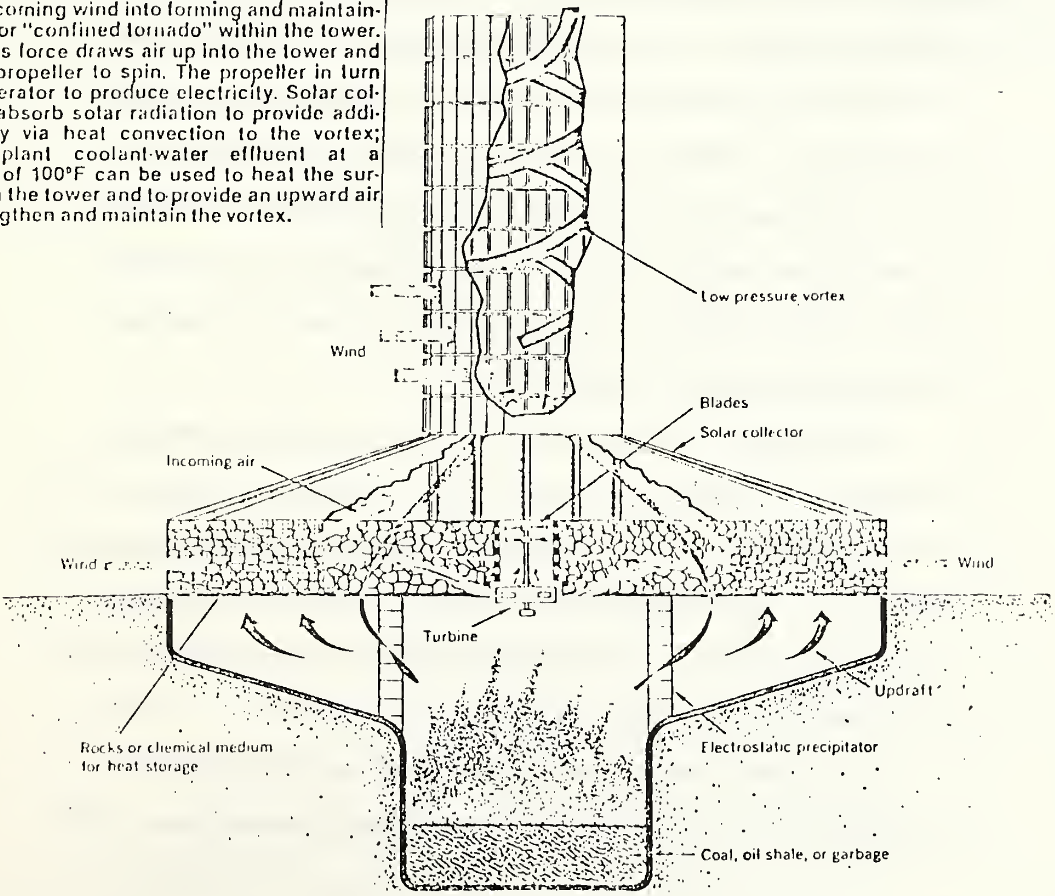

Low pressure vortex
Wind
Blades
Solar collector
Incoming air
Wind
Wind
Turbine
Updraft
Rocks or chemical medium for heat storage
Electrostatic precipitator
Coal, oil shale, or garbage

Fig. 9

Claimed advantages of such a system are:

1. A large power augmentation factor, i.e. small turbine size for a given power output
2. A stationary, omnidirectional structure.

It is necessary, however, for the vanes to be moveable so as to open on the windward and close on the leeward sides of the tower.

An additional advantage claimed for this system is that it can be used to generate power when the wind is not blowing by adding heat at the base of the tower. The resulting updraft lowers the pressure within the tower and draws air throught the turbine, just as the updraft in a smokestack draws air through a fireplace or furnace. This is in effect a very low temperature heat engine of very low efficiency, however, and hence depends upon having a heat source that is essentially "free," for example solar radiation or heat rejected by a fossil fueled powerplant.

The behavior of a vortex is notoriously hard to predict accurately. Large effects predicted by the usual two-dimensional theory are often not observed in practice because of three-dimensional effects that are hard to predict in advance. Thus, experimental verification of performance claims is essential.

The chief proponent of the "tornado" concept is Dr. James T. Yen of Grumman Aerospace Corporation. He reports[1] that experiments done with small towers up to 3 feet high and turbine diameters of about 4 inches have yielded power augmentation by a factor of 10 to 15. In principle, higher performance should be obtained from systems of larger size. According to Dr. Yen a tower for the production of 100 to 10000 megawatts would be about 600 feet in diameter and 2000 feet high, i.e. comparable in height to the highest skyscrapers. It is estimated to cost about the same as a conventional fossil fueled powerplant. He claims that the system, while large, is structurally simple and cheap to fabricate and assemble. He also notes that many small towers may be preferable to a few large ones but the tradeoffs in terms of cost and performance are not stated and probably are not yet known.

In summary, the tornado concept has, on a laboratory bench scale, demonstrated significant power augmentation. However, because the aerodynamics of vortex flow is not easy to predict, it is not easy to predict the performance of larger systems until field trials of larger systems have been carried out. As compared to an augmentation system utilizing baffles, diffusers or wing-tip vortices it has the advantage of achieving omnidirectionality by moving many relatively small vanes rather than the whole structure. However, it is not yet clear whether this is cheaper than a rotating structure or cheaper than an unaugmented windmill. It is almost certain to be more expensive than a fixed structure designed to accommodate only small changes in wind direction."

[1] James T. Yen, IEEE Spectrum, pp.42-47, March 1978.

APPENDIX D

One of the conditions of my DNR Grant was that I visit Prof. William Hughes at Oklahoma State University and observe their wind energy project. Later I was told that this trip was optional, but I considered it a good idea and arranged a visit for May 12, 1978.

This project was managed by Prof. Hughes and Dr. R. Ramakumar of the Electrical Engineering Department. They started in wind energy in the 1960's with small grants from Oklahoma utilities. Then they got one of the first Federal grants, at the same time that Ralph Powe of the MSU Mechanical Engineering Dept. got a grant to study a system based on sail-carrying cars running on an oval track. The Oklahoma grant was terminated about a year ago because the sponsor has lost interest in variable-speed wind machines, and the Oklahoma field-modulated alternator concept was developed specifically for such machines.

This system is based on a specially-built alternator in which the field is modulated at 60 Hz while the alternator is allowed to run at variable speed. The alternator output then contains a 60 Hz component. Components at other frequencies are filtered out. (I have tried this method with the Delco automotive alternator. It is possible to modulate the field current at 60 Hz, but the magnetization in the iron in the field poles has too long a time constant for response to changing field current at this frequency.)

Ramakumar demonstrated this machine for me, running its output into a bank of light bulbs. It puts out 60 Hz at a voltage proportional to its rpm, but could be provided with constant voltage output over a two-to-one speed range by varying field magnitude. (This speed range is not sufficient for efficient operation of wind rotors over the range of usable wind speed, if rotor pitch control is not provided.) Ramakumar said that the field-modulated system is best suited for the 10 to 100 kW power range; for smaller systems the control becomes too expensive. Fig. 10 shows this system, with the alternator at left and the filter at right. They have also developed a larger, 3-phase 120 volt, system for the Air Force which I believe has 10 kW capacity.

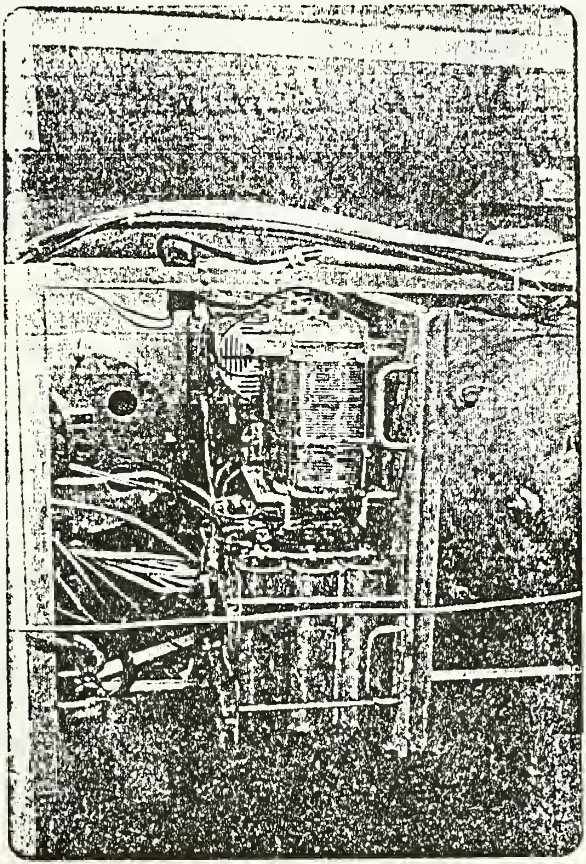


Fig. 10

Development and test of this larger alternator and of the wind rotors took place at the Stillwater Airport. This alternator work took place in a large, roomy building which is now idle. Tests of the complete systems took place at the site shown in Fig. 11, which shows Dr. Ramakumar next to a sign listing the project title and sponsors.

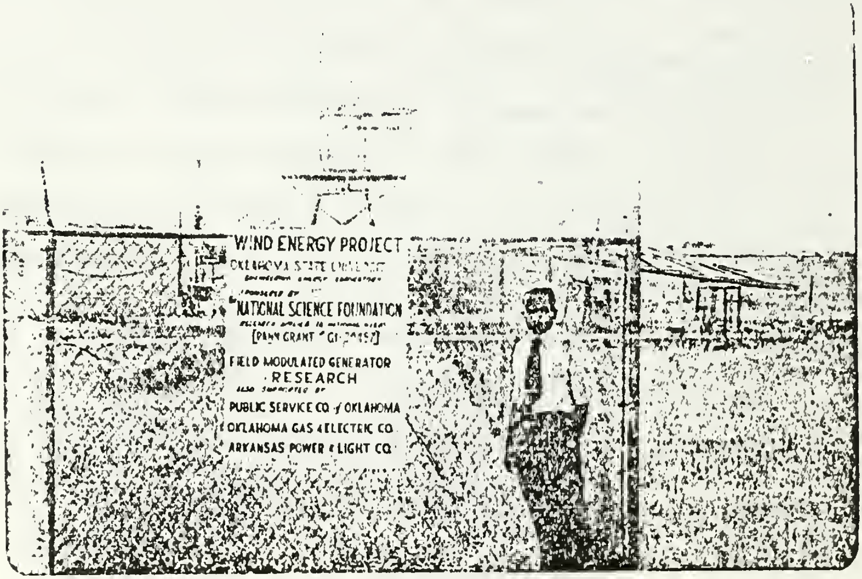

WIND ENERGY PROJECT
OKLAHOMA STATE UNIVERSITY
NATIONAL SCIENCE FOUNDATION
FIELD MODULATED GENERATOR
RESEARCH
PUBLIC SERVICE CO. of OKLAHOMA
OKLAHOMA GAS & ELECTRIC CO.
ARKANSAS POWER & LIGHT CO.

Fig. 11

The large rotor is at the right in Fig. 11, its tower at the center, and the small rotor mounted on its pole appears at the left. A better view of the large rotor and its tower is shown in Fig. 12. The building used for alternator construction and testing appears in the background. There was no provision for this rotor, which is of about 30-foot diameter, to face the wind. The rotor was attached about halfway up the tower, low enough so that the guy cables attached to the top of the tower would clear the rotor.

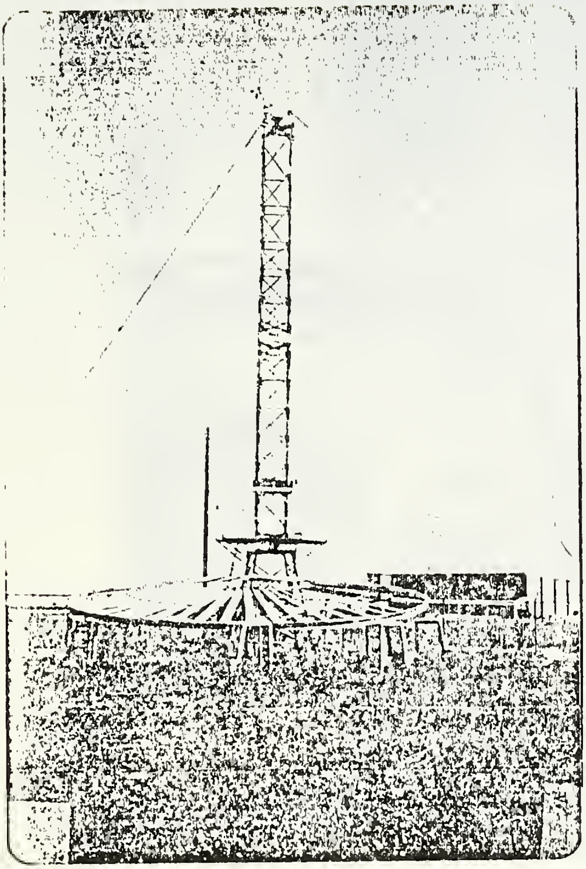


Fig. 12

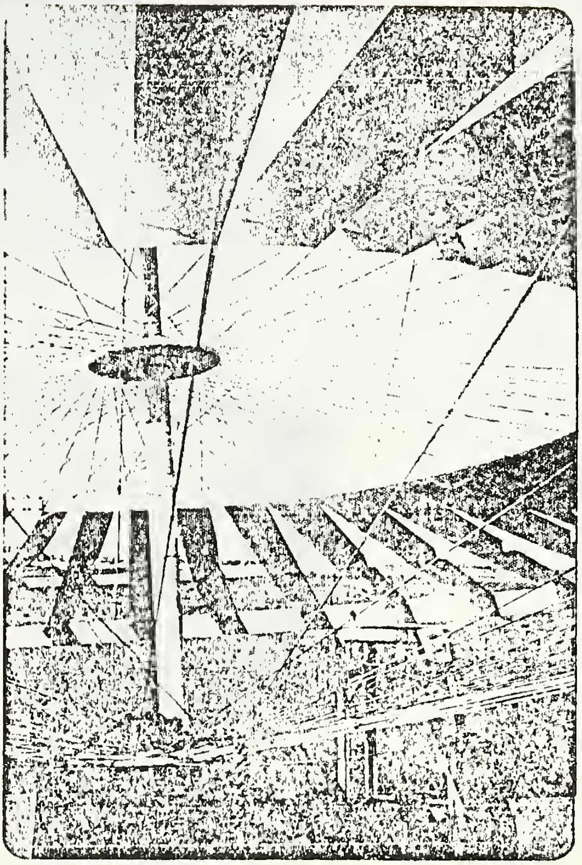


Fig. 13

A close-up of the center of this rotor is shown in Fig. 13. The rotor is of the Chalk bicycle-wheel design. Spokes run from the hub through an inner ring. Between this ring and the outer rim, thin and soft aluminum sheet is bent in airfoil shape around each pair of spokes. It appeared that there was difficulty with spokes breaking and aluminum blades bending.

An edge-on view of this rotor (with me in front to indicate size) can be seen in Fig. 14. The channel-shaped rim serves to anchor the spokes and also acts as a pulley for the belt which drives the alternator.

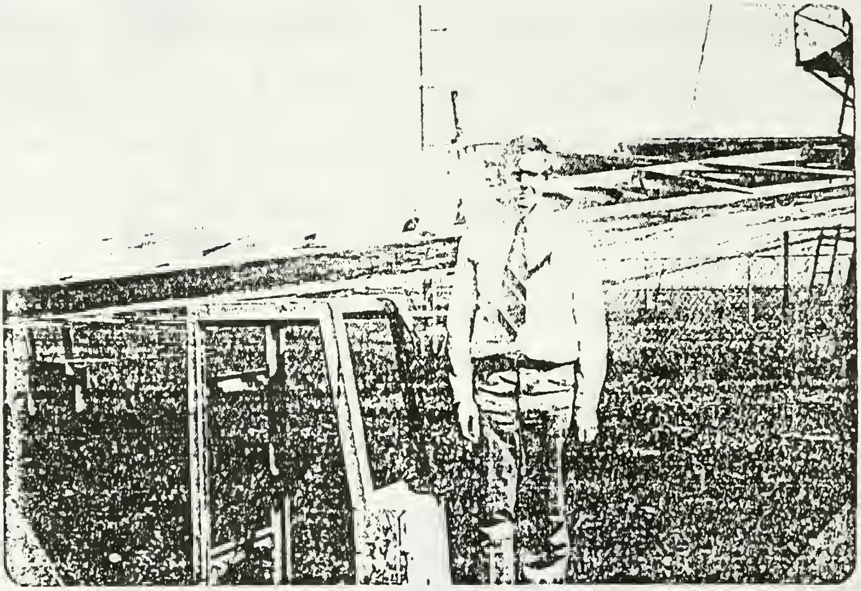


Fig. 14

The smaller, 15-foot diameter rotor mounted on its pole is shown in Fig. 15. The fin actuates a drive motor which turns the pole and rotor to face the wind. Quite a few wires are connected to the alternator, so instead of using slip rings, the wires were connected by a loose cable and a stop was provided to prevent the pole from rotating too far. The main bearings for the rotor run on a horizontal shaft extending from the mast. Another 15-foot rotor of this type is at the site, but does not appear in these photos.

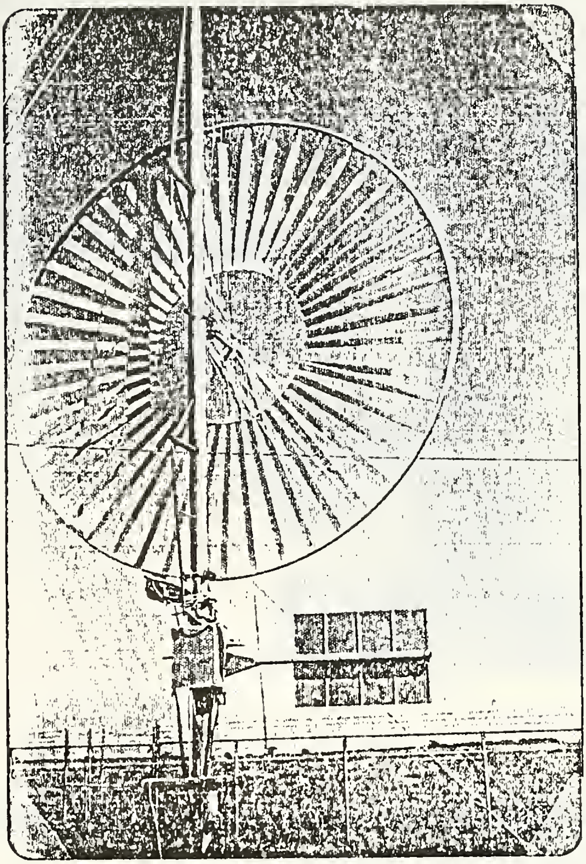


Fig. 15

A close-up of the rim, the alternator, and the pole rotation drive appears in Fig. 16. At this time the rotor was wired to the alternator to prevent rotation, and the pole drive also was not in operation.

In Fig. 17, channel sections for the 15-foot rotor can be seen, as well as the drive belt which is about 1/8" thick and 2½" wide.

Ramakumar gave me a copy of the final report on this project. It seems a shame that funds were not provided for life testing of this system. Ramakumar informed me

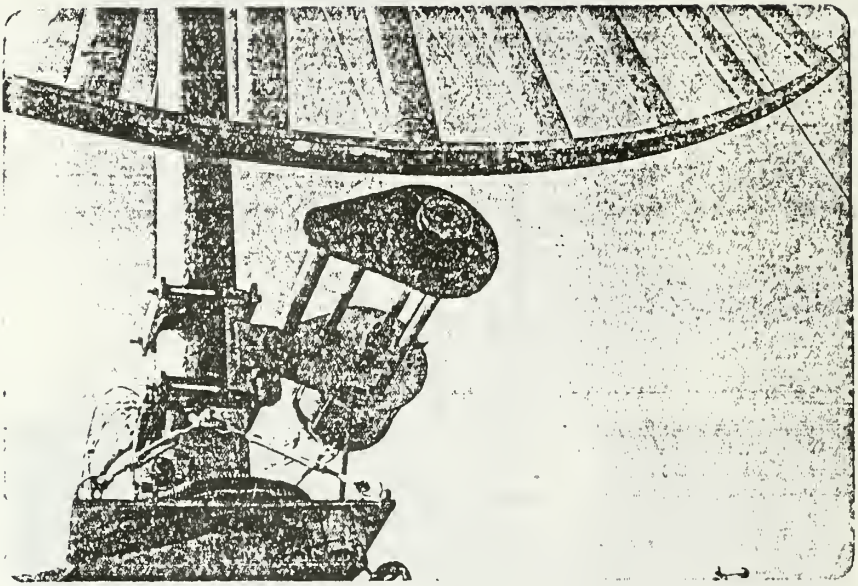


Fig. 16

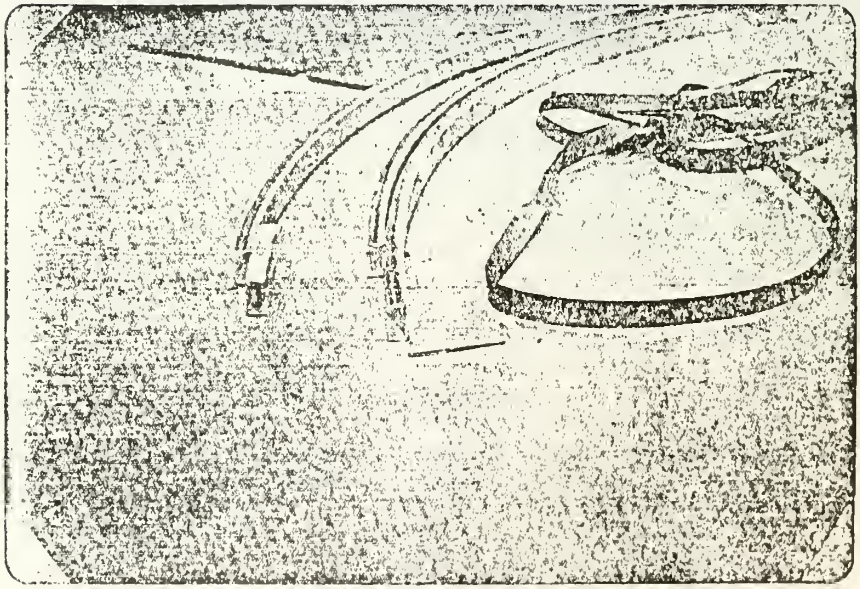


Fig. 17

of a Federal program to test various windmill designs at Rocky Flats, Colorado, but this seems a poor substitute

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